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TRACKING AND DATA RELAY SATELLITE SYSTEM CONFIGURATION AND TRADEOFF STUDY–PART II FINAL REPORT

Volume IV
Space Shuttle Launched TDRSS

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16. Abstract

Configuration data and design information for the Space Shuttle launched configuration is contained herein. It treats the overall system definition, operations and control, and telecommunication service system including link budgets. A brief description of the user transceiver and ground station is presented. A final section includes a summary description of the TDR spacecraft and all the subsystems. The data presented are largely in tabular form for easy reference.

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1. SYSTEM DEFINITION

1.1 INTRODUCTION

A Space Shuttle launched TDRSS concept is described in this volume.

- Section 1, System Definition, identifies the system concept, the spacecraft configuration, and the telecommunication service.
- Section 2, Operations and Control, contains an orbit insertion profile, a brief description of the spacecraft on-orbit control, including a listing of auxiliary propulsion and a description of the telecommunications service operation.
- Section 3, Telecommunication Service System, contains a summary of the telecommunication services and link budgets as well as general TDRS repeater characteristics. It also contains a brief description of the user transceiver and ground station design. Considerable use of the analysis contained in Volume 3 has been made in arriving at the results contained in this section.
- Section 4, TDR Spacecraft Design, is comprised of three subsections:

  4.1 Design concept discusses the spacecraft design objectives and the requirements and the implementation of the telecommunication service system.

  4.2 Configuration Summary is a discussion of the TDR spacecraft design characteristics including an artist's concept of the spacecraft and a spacecraft configuration drawing. This section also contains a compilation of the spacecraft parameters, electrical power budgets, mass summaries, and a list of the subsystem components.

  4.3 Subsystem Description contains descriptive material of the subsystem design and a summary of pertinent data, namely, subsystem block diagrams, requirement tables, and mass summaries.

1.2 SYSTEM CONCEPT

The TDRSS concept employs two geostationary satellites to provide relay links for telemetry, tracking, and command (TT&C) between multiple low earth-orbiting user satellites and a centrally located ground station, as shown in Figure 1, making possible nearly continuous reception of data in real time.

The TDRSS comprises the following major elements:

- GSFC network scheduling and data processing facilities
- TDRS ground station
- TDRS control center
- Two operational TDR satellites, one in-orbit spare

The communication links from the ground station to the TDRS to the user are defined as forward links, and the links from the user spacecraft to the TDRS to the ground station are defined as return links.

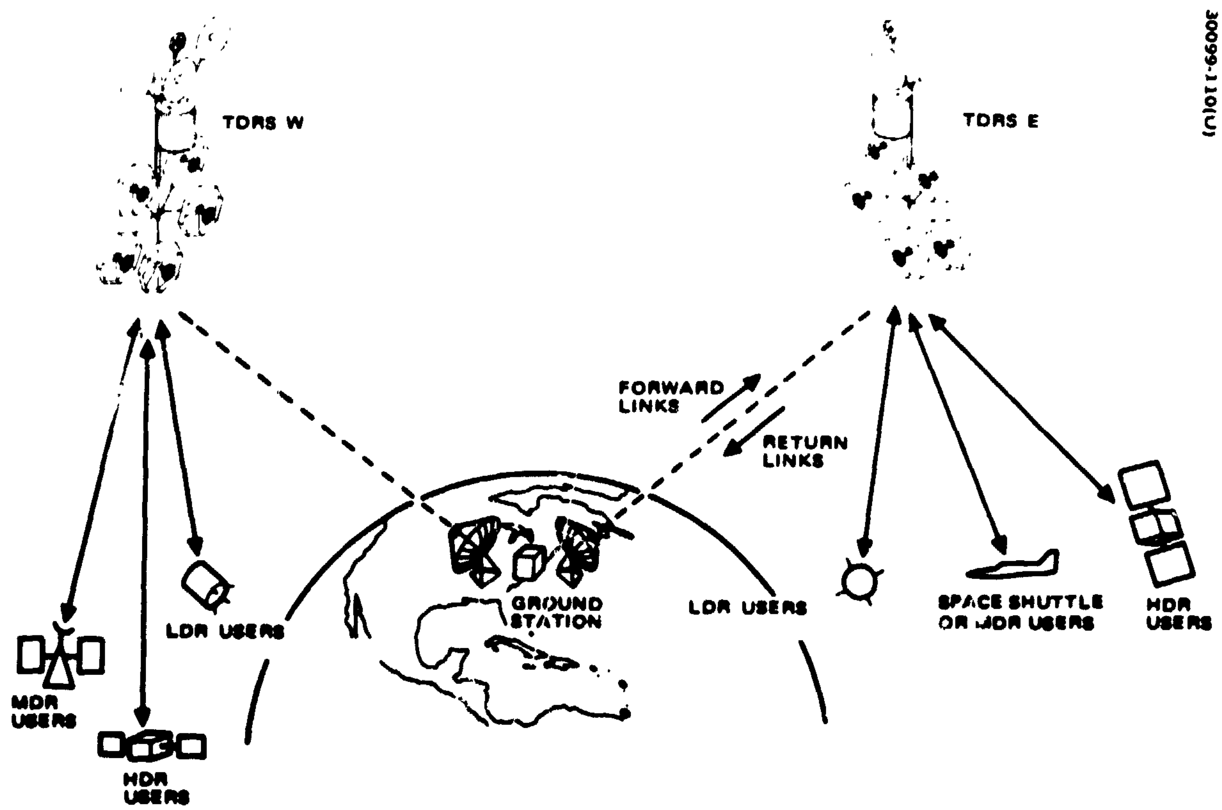

Figure 1. TDRS System Concept

The forward links contain user command, tracking signals, and voice transmissions; whereas the return links contain the user telemetry, return tracking signals, and voice.

The users are categorized as low data rate (LDR), medium data rate (MDR), and high data rate (HDR), according to their telemetry rates.

The Space Shuttle launched TDRSS concept is unique in that all three TDR spacecraft will be deployed with one Space Shuttle flight. Namely, the shuttle injects the three TDRS attached to a Transtage into a low altitude circular earth orbit. Following separation from the Space Shuttle, the Transtage injects all three spacecraft into a transfer orbit with the apogee at synchronous altitude. The mission profile for each spacecraft after separation from the Transtage is that of a typical synchronous satellite (e. g., Intelsat IV).

1.3 TDRS CONFIGURATION SUMMARY

The baseline configuration selected for the Space Shuttle launched TDRSS is similar to the Atlas-Centaur launched TDRSS configuration (see Figure 2). However, the relatively large payload bay of the Space Shuttle permits a considerably easier stowage of the antenna subsystem, namely, stowage of the antennas around the solar cell array. Accordingly, a tandem arrangement of the multiple launched spacecraft is feasible.

The Hughes Gyrostat stabilization concept provides a fully stabilized platform for the payload, while exploiting the simplicity and long-life advantages associated with spinning satellites. This configuration features despun platforms at both ends of the spacecraft to facilitate deployment of the antennas. Antennas are mounted off the platforms on mast type support structures. The despun section also houses the communication equipment and some of the telemetry, tracking, and command equipment. Electronic equipment is mounted on thermally controlled shelves.

The spinning section of the spacecraft houses the electrical power subsystem, attitude and reaction control subsystems, and a larger portion of the telemetry, tracking, and command subsystem. The electrical power subsystem has been sized to provide continuous voice communication service in order to take advantage of the payload capability of the Space Shuttle and to maximize communication service.

The Transtage was selected to provide a cost-effective booster to inject an assemblage of three spacecraft simultaneously into synchronous transfer orbit. The injection capability is approximately 6600 kg. Each spacecraft has been allocated 2100 kg, allowing 300 kg for mission-peculiar equipment and installation onto the Transtage.

1.4 TELECOMMUNICATION SERVICE

The TDRS repeater includes electronics for three MDR links. It is assumed that as a baseline, only two links are required and that the third set

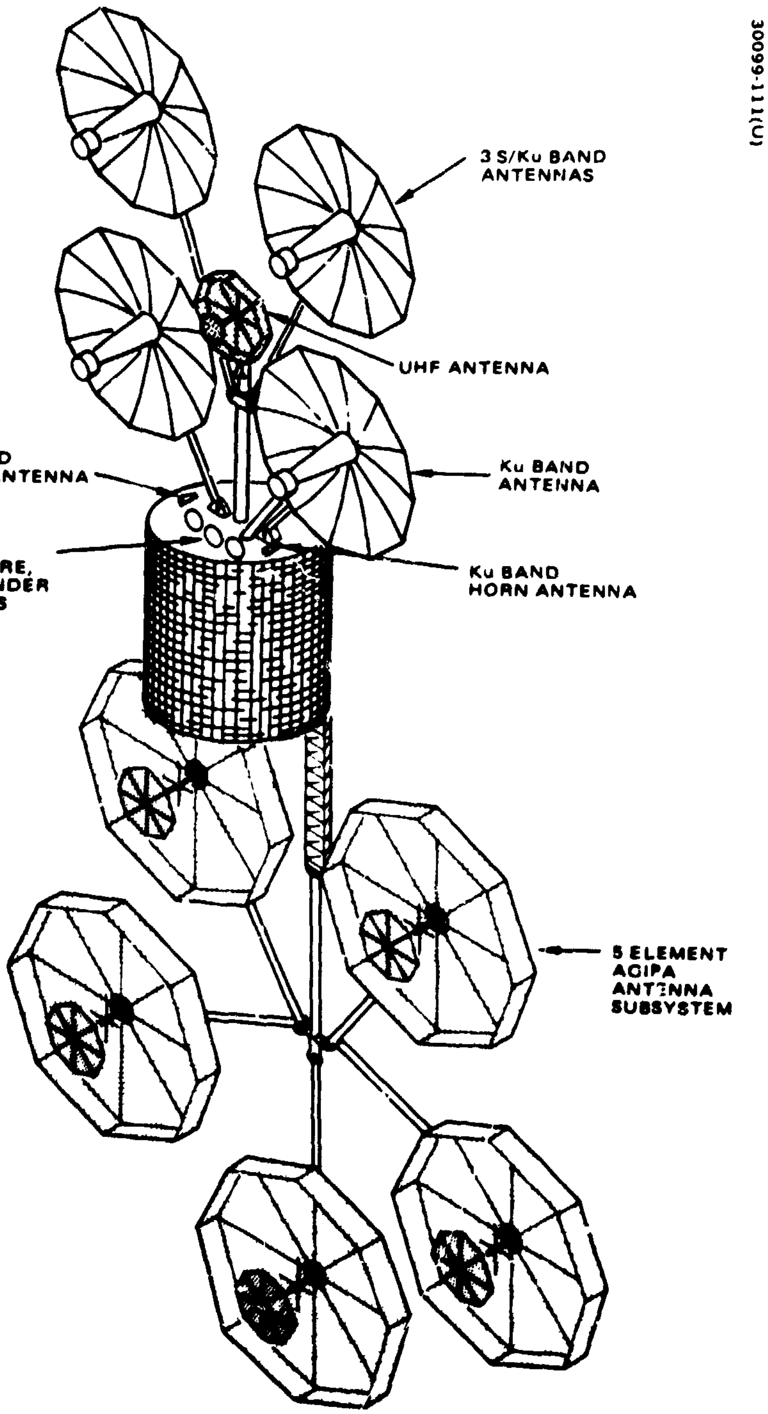

Figure 2. TDR Spacecraft Configuration

of electronics is simply a redundancy. It is possible to operate with three MDR links since there is an adequate contingency in the power budgets; however, such an operation will have an impact on the spacecraft reliability and also on the availability of the HDR service (recall that only three dual-feed S/Ku band antennas are available).

The user service provided is summarized in Table 1.

TABLE 1. TDRSS USER SERVICE

Low data rate (LDR) service	Forward, UHF	Sequential to one user at a time
	Return VHF	Simultaneous from all users, AGIPA for added RFI suppression
LDR voice*	Forward, UHF	Continuous service available with one user
	Return, VHF	
Medium data rate (MDR)** service S band	Forward	Two links. One continuous link at an EIRP of 47 dBW* One continuous link at an EIRP of 41 dBW
	Return	Two links, 1 Mbps maximum each
High data rate (HDR)** service Ku band	Forward	Two links at an EIRP of 59 of 51 dBW continuous
	Return	Two links, 100 Mbps maximum each

*The LDR forward voice and the MDR forward links at an EIRP of 47 dBW can not be operated simultaneously. However, both MDR forward links may be operated at an EIRP of 41 dBW simultaneously with the LDR forward voice.

**Separate transmitters and receivers are provided for MDR and HDR service; however, only three antennas (with dual feeds) are used for both types of services. Thus, the possible service combinations are:

- Two MDR users and one HDR user
- One MDR user and two HDR users
- One MDR user and one HDR user with time sharing between one additional MDR and one additional HDR user
- Two MDR users and two HDR users if one MDR and one HDR user remain within one antenna beam (i.e., at the same spatial location).

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2. OPERATIONS AND CONTROL

The TDRS operations and control involve three major functions:

- TDRS launch and orbital deployment
- TDRS on-orbit control
- TDRSS telecommunication service operations.

Each of these topics will be discussed briefly in the following sections.

2.1 TDRS ORBIT INSERTION PROFILE

The current plan is to launch all three TDR spacecraft in one Space Shuttle flight. Since the Space Shuttle flights will terminate in a low altitude circular earth orbit, the next mission phase — injection into transfer orbit — requires the use of a suitable chemical stage. Three candidate stages — Agena, Transtage, and Centaur — were reviewed (see Table 2).

TABLE 2. MASS IN SYNCHRONOUS ORBIT FOR SEVERAL PROPULSION OPTIONS

Propulsion Stages	Mass In Synchronous Orbit, kilograms
Agena plus apogee motor	2025*
Transtage plus apogee motor	3345*
Centaur	6380

*Excludes apogee motor expendables.

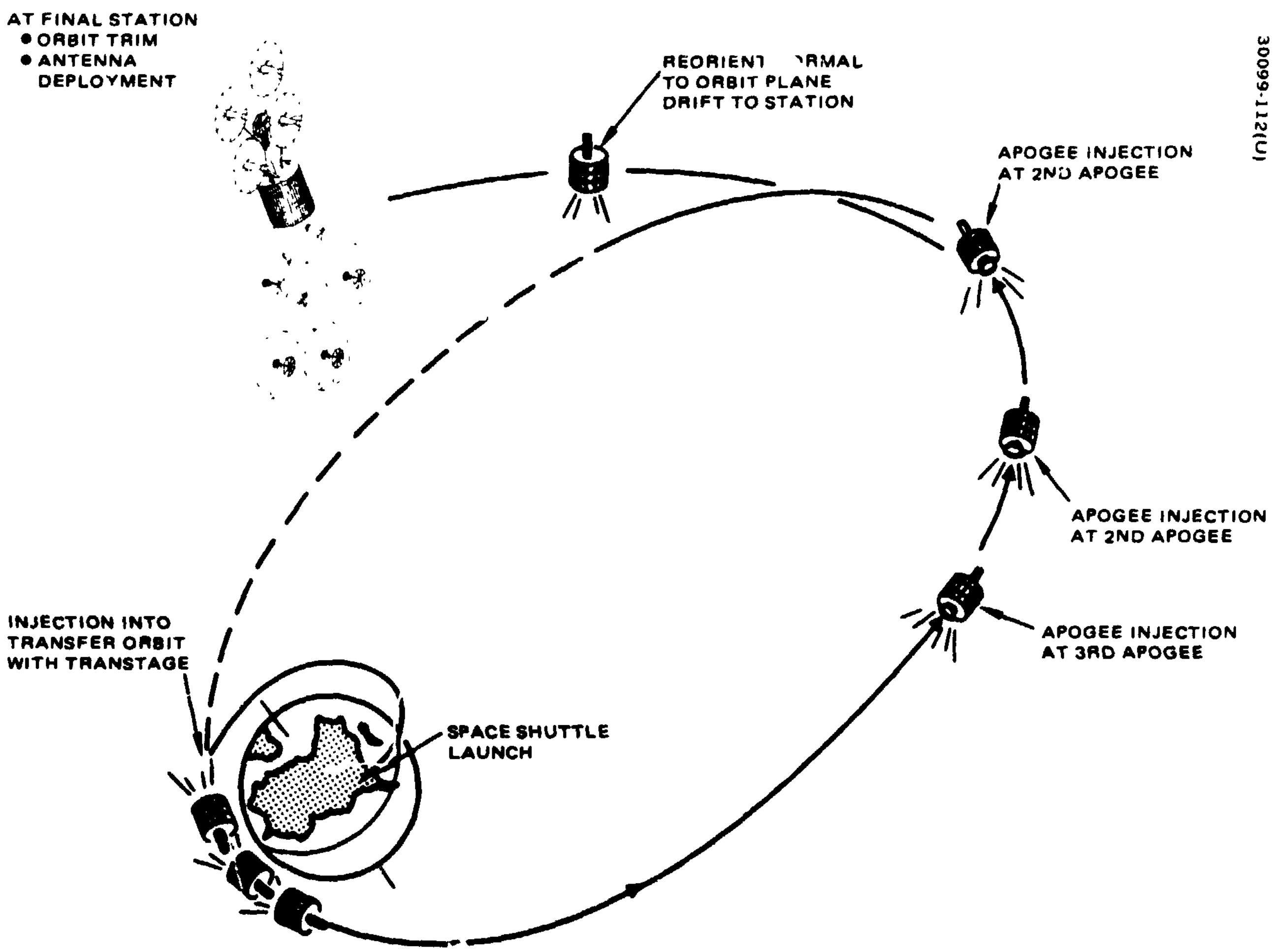

Figure 3. TDRS Orbit Insertion Profile

The combined synchronous orbit mass of the three TDR spacecraft is in the neighborhood of 3100 to 3200 kg, which as seen from Table 2, requires a Transtage and an apogee motor in each spacecraft or a Centaur. Although accurate costs are difficult to ascertain, indications are that the use of the Transtage plus apogee motors would result in well over $1 million savings over the Centaur. Therefore, the Transtage plus apogee motors for each spacecraft was the selection for this TDRS configuration.

The Space Shuttle launched TDRSS mission profile consists of the following phases:

1) Space Shuttle launch of all three TDRS due east into a low altitude circular parking orbit.

2) Injection into a synchronous transfer orbit at the first node. The Transtage injects all three spacecraft into synchronous transfer orbit. Following injection, the individual spacecraft are separated and spun up. A small relative velocity, say 2 m/s, imparted at separation will ensure that the spacecraft are separated by some 40 km at apogee.

3) The transfer orbit phase for each spacecraft will be similar to typical synchronous communication satellite missions (e. g., Intelsat IV) and will not be discussed in this report.

4) The apogee injection is scheduled to minimize the time required to drift to station. The nominal plan is as follows:

   - Fire apogee motor of TDRS E at second apogee and drift 5 degrees (from 50 degrees west to 45 degrees west, to station in 2 ±1 days.

   - Fire apogee motor of TDRS spare at second apogee and drift 55 degrees (from 50 degrees west to 105 degrees west) to station in 50 ±20 days.

   - Fire apogee motor of TDRS W at third apogee and drift 42 degrees (from 210 degrees west to 168 degrees west) to station in 16 ±6 days.

5) Drift to station and station acquisition will be similar to typical synchronous satellite missions (e. g., Intelsat IV) and will not be discussed in this report.

6) Antenna deployment is discussed in Section 4. 3. 3.

7) On orbit operations are discussed in Sections 2. 2 and 2. 3.

A typical mission profile is shown in Figure 3.

2.2 TDRS ON ORBIT CONTROL

There are two systems for TDRS telemetry and command: Ku band and S band. The Ku band system is prime with the S band system, which employs an omni antenna on the TDRS for backup.

TDRS tracking can be accomplished by using either the LDR forward link or the S band transponder. Using the former, a signal is continuously sent to each TDRS via the Ku band system. Each TDRS repeats the signal at UHF via the broad coverage antenna. A relatively low gain UHF antenna can be used to receive these signals at the ground station, where they are processed to provide range and range rate measurements for the TDRS. The S band transponder has an earth coverage antenna and is well suited to trilateration ranging. It is also compatible with the Goddard range and range rate system.

The on-orbit control operations for the TDRS are:

- East-West stationkeeping
- Attitude maneuvers
- S band and Ku band antenna pointing
- TDRS repeater channel settings for MDR users

The frequency of east-west stationkeeping maneuvers is approximately one maneuver every 100 days and the frequency of the attitude maneuver is one maneuver every 2 days. The satellite has sufficient angular momentum so that antenna pointing will not require any attitude correction maneuvers. The stationkeeping and attitude correction maneuvers do not require an interruption of the telecommunication service to the users. Table 3 is a summary of the requirements imposed on the auxiliary propulsion.

TABLE 3. AUXILIARY PROPULSION REQUIREMENTS

ΔV				129 m/s
Cumulative impulse predictability			< 10 pulses	20 percent
			> 50 pulses	10 percent
Burn time:	Steady state			None
	Pulse	Axial		70,000
		Radial		30,000
Cold starts:		Axial		1250
		Radial		30

The ground link antenna has autotrack capability and under normal conditions will require no ground control. Three dual feed antennas (S and Ku band) are provided for MDR and HDR service. For MDR users, the antennas are pointed by commands from the TDRS Control Center. The antenna beamwdith of 2.5 degrees allows relatively infrequent pointing adjustments, i.e., no more often than once every 20 seconds. For HDR service, autotracking is implemented. The antennas have tracking Ku band feeds but must be slewed to their acquisition position for each HDR user pass. The scan motion for link acquisition will be generated in the TDRS and will only need an activation command from the TDRS Control Center. All antenna pointing, slewing, and acquisition commands will be based on spacecraft ephemerides and a master schedule for TDRSS services.

2.3 TDRS TELECOMMUNICATION SERVICE OPERATIONS

The TDRS system consists of five major elements:

1) GSFC communication control and processing facility, referred to as GSFC

2) Satellite control centers for users and TDR spacecraft

3) Ground station

4) Tracking and data relay satellites

5) User spacecraft.

The overall functional relationship among these elements is shown in Figure 4. Note that GSFC has the responsibility for scheduling the TDRSS communication services and providing most data processing. The TDRSS link availability will be defined by Network Scheduling and Control similar to the present NASA ground station scheduling and will be forwarded to the users on a regular schedule. During the scheduled times, the user spacecraft command data are compiled at the GSFC Control Center into a forward link data stream that is sent to the TDRS ground station for transmission to the user spacecraft.

The TDRS Control Center computes commands for the TDR satellites and forwards commands to the ground station for transmission to the satellites. These commands configure the repeater and point the steerable antennas as well as produce housekeeping and subsystem control functions. Each user control center will issue commands to assigned spacecraft, limited only by the predetermined schedule.

The ground station is the interface between the TDRS Control Center, GSFC, and the TDR satellites. All modulation/demodulation, multiplexing/demultiplexing, and RF transmitting/receiving is performed at this facility.

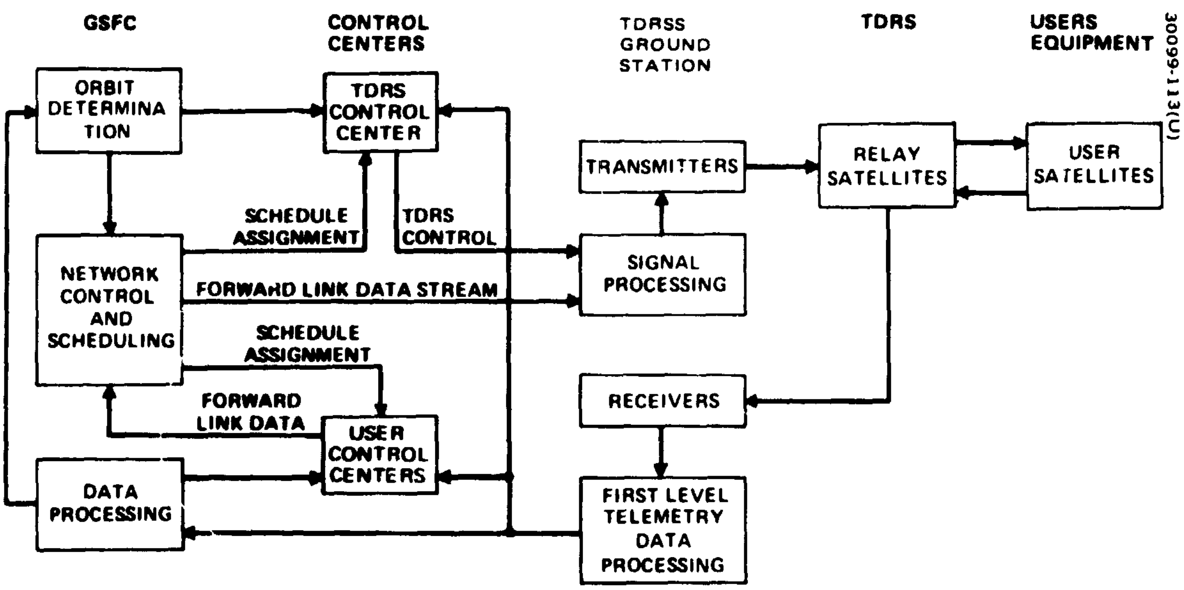

Figure 4. TDRSS Functional Operations

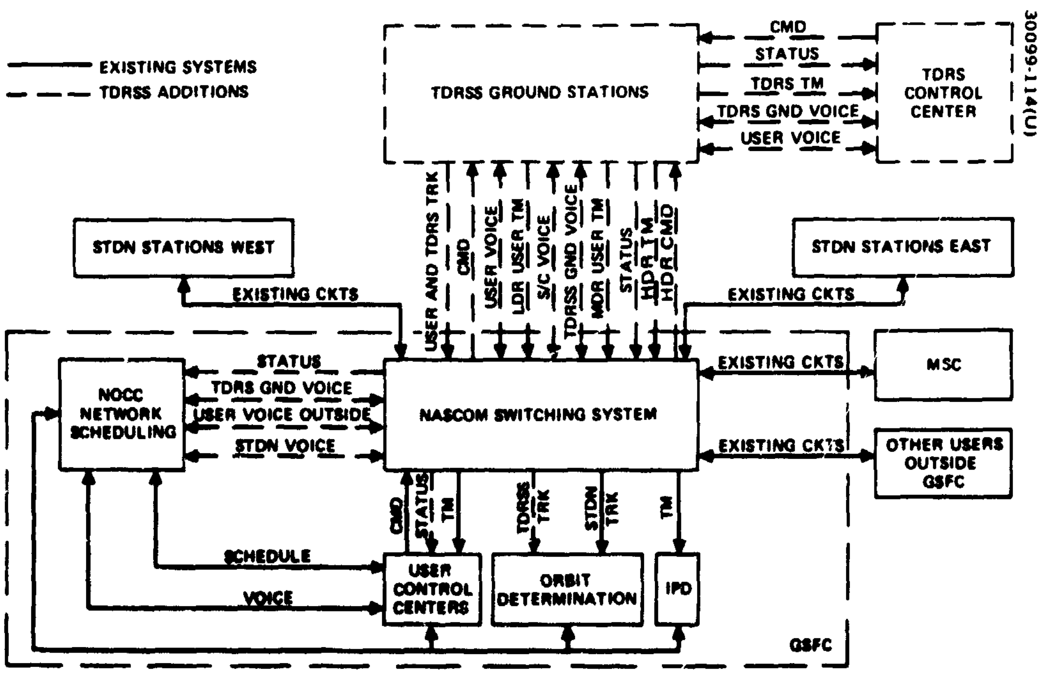

Figure 5. TDRS Ground Network

The return link data can be sent directly to the user program offices and/or to GSFC for further data processing. Orbit determination for both the TDRS and user satellites is performed at GSFC and made available to the user program offices and to the TDRS Control Center.

Figure 5 illustrates how the TDRSS augments the current ground network and employs much of the existing scheduling, switching, and data processing capability of GSFC. The control center operations are listed in Section 2. 2. The major ground station functions include:

- Ground station antenna pointing
- Transmitting to and receiving from TDRSs
- Demultiplexing signals from GSFC into forward link channels plus additional status, scheduling, and control signals
- Spreading spectra of forward link signals as required
- Carrier modulation
- Filtering and processing as required to separate received signals and to reduce RFI in LDR return channels
- Configuration of demodulation equipment according to schedule for all services
- Multiplexing of all return link signals, range, and range rate measurements, and status data for transmission to GSFC
- Internal forward links verification, comparing what was transmitted to the TDR satellites in each link to outputs of forward link demultiplexer

The LDR return link service is operationally the most difficult because there will be many telemetry signals simultaneously present in the ten channels from each TDRS. The choice of which TDRS channels to connect a particular user's processing and demodulation equipment is made initially at GSFC and may be automated, based on the GSFC handover schedule. MDR and HDR functions are conceptually the same as for the LDR, but only one signal per TDRS at any time will be received per channel, and acquisition and demodulation will be simpler.

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3. TELECOMMUNICATION SERVICE SYSTEM

The telecommunication service system consists of the communication equipment in the TDRS, user spacecraft, and TDRS ground station. The services and their operational aspects have been briefly discussed above and are depicted in Figure 6. The frequency plan is shown in Figure 7. The telecommunication services provided via each TDRS are summarized below.

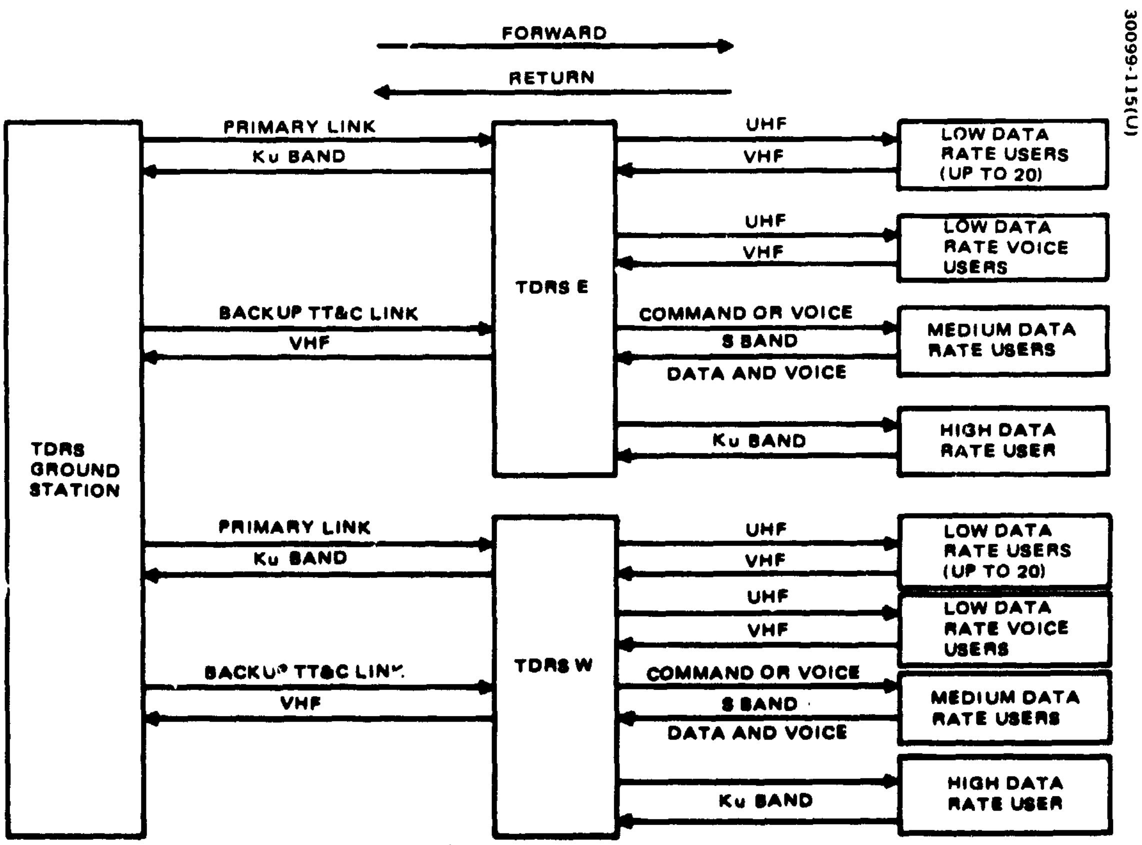
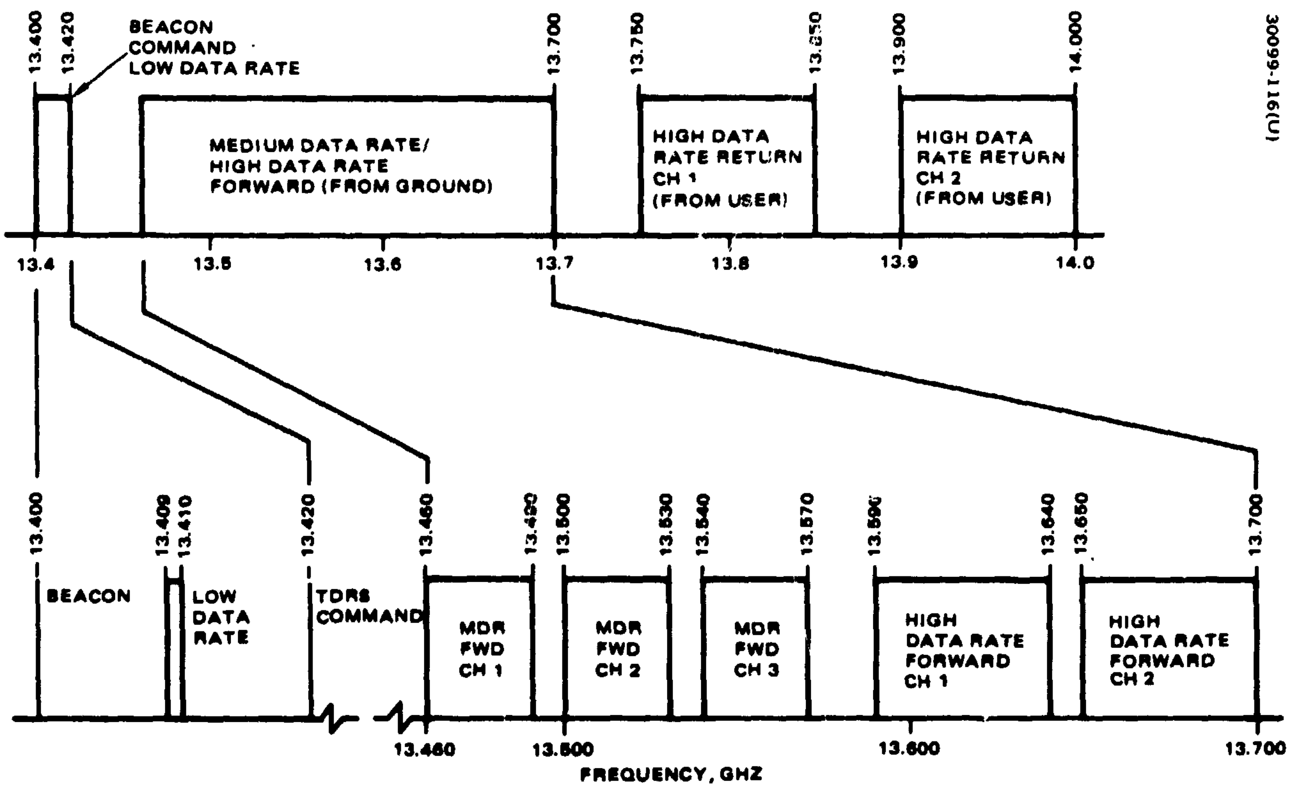
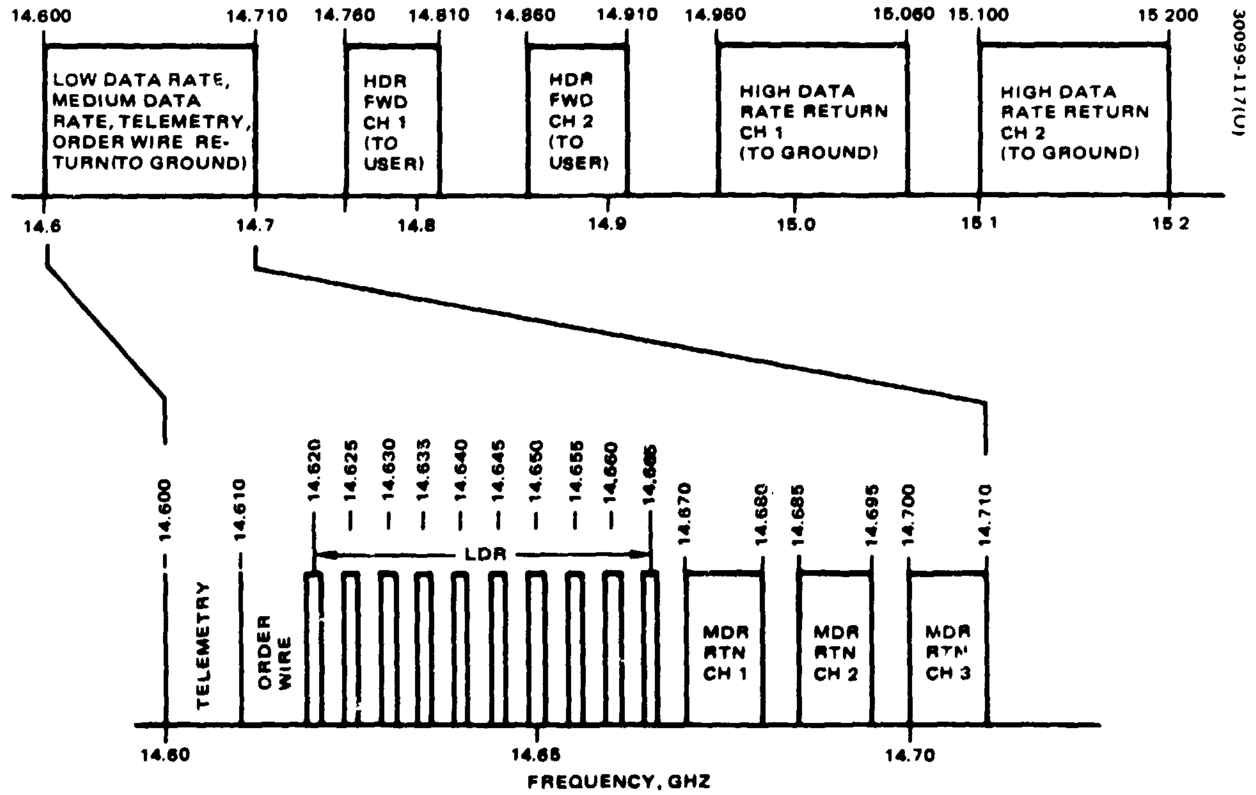


Figure 6. Telecommunications Service System

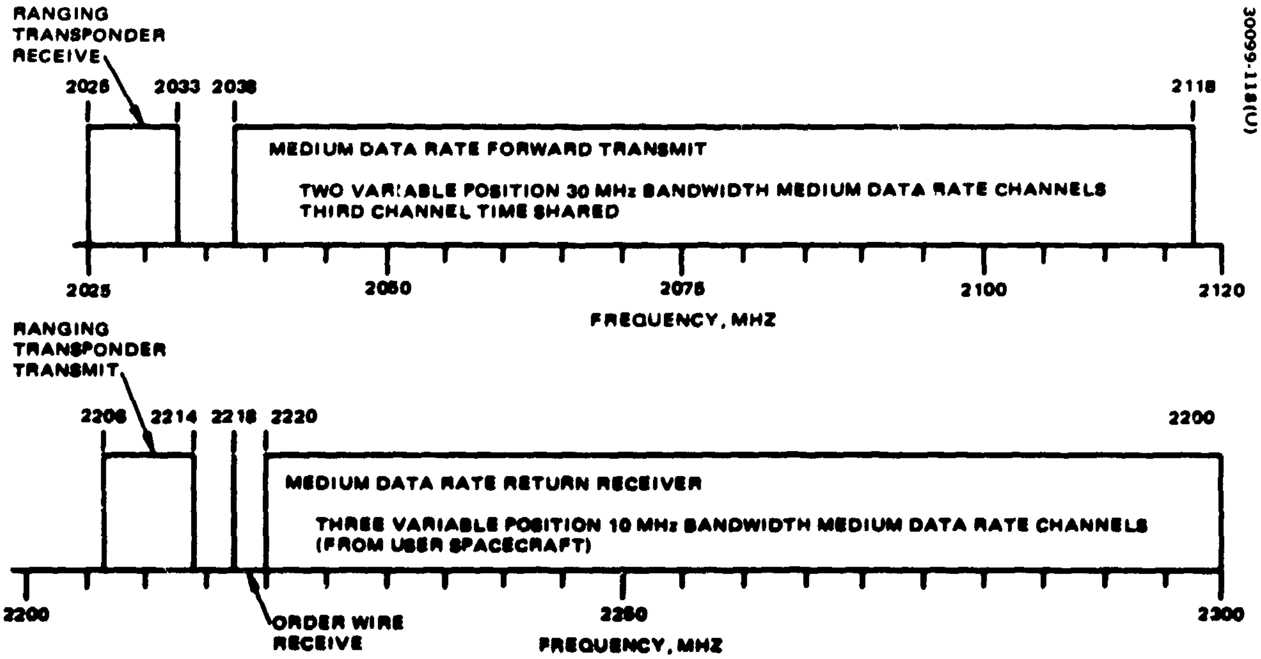


a) Ku Band Receive

Figure 7. Frequency Plan



b) Ku Band Transmit



c) S Band Transmit and Receive

Figure 7 (continued). Frequency Plan

3.1 SERVICES AND LINK PARAMETERS

This section consists of two major subsections. Subsection 3.1.1 presents a very brief summary of the services provided by the TDRSS. Subsection 3.1.2 contains the major assumptions, characteristics, parameters, and parametric relationships associated with each of the services LDR, MDR, HDR, order wire, and S band transponder. Following these, the parameters of the TDRS/ground station link are listed. The link power budgets, which are the basis for all link analysis and service capability, are presented in Tables 4 and 5.

3.1.1 Services

3.1.1.1 Low Data Rate at UHF/VHF

- Command of, tracking of, and telemetry from up to 20 users; command is sequential, tracking and telemetry are simultaneous for all users.
- Two-way voice to a manned spacecraft with an omni antenna.
- Command and voice services can be provided simultaneously.

3.1.1.2 Medium Data Rate at S Band

- Three simultaneous two-way links, each with the following capability:

  Forward links: Two 24 kbps delta modulated voice signals plus 2 kbps data to the Space Shuttle (this service is restricted to 50 percent usage and corresponds to a high power transmitter mode) or up to 2 kbps data continuously to an unmanned user spacecraft with a 0 dB gain antenna.

  Return links: Up to 1 Mbps data from a user spacecraft.

3.1.1.3 High Data Rate at Ku Band

- Two simultaneous two-way links, each with the following capability:

  Forward links: Up to 50 Mbps

  Return links: Up to 100 Mbps data from a user spacecraft

3.1.1.4 Order Wire at S Band

- An S band antenna has been provided for an order wire service. This is a broad coverage antenna, thus a request can be made by a manned spacecraft with an omni antenna for MDR service, even if the TDRS narrowbeam S band antenna is not pointed at this user. The order wire service channel bandwidth is 1 MHz.

TABLE 4. TDRS TRANSMIT LINK BUDGETS

Parameters	LDR Command UHF	Voice UHF	MDR Forward S Band High Power	MDR Forward S Band Low Power	Ground Ku Band	HDR Forward Ku Band
TDRS EIRP, dBW	30.0*	30.0	47.0	41.0	EIRP	59
TDRS pointing loss, dB	-	-	-0.5	-0.5	-0.5	-0.5
Space loss, dB	-177.5	-177.5	-192.0	-192.0	-208.4	-208.9
Receive antenna gain, dB	-3.0	-1.0	G_u	G_u	63.0	G_u
Receive pointing loss, dB	-	-	-0.5	-0.5	-0.5	-0.5
Receive line loss (L), dB	-0.5	-1.0	-2.0	-2.0	-0.3	-2.0
Receive ellipticity loss, dB	-3.0	-1.0	-1.0	-1.0	-0.2	-0.2
Receive power, P_r, dBW	-154.0	-150.5	G_u-149	G_u-155	EIRP-146.9	G_u-3.1
Receiver noise figure, dB	3.75	3.75	5.1		3.8	7.0
Receiver noise temperature, K	400.0	400.0	650.0		400.0	1160.0
Background noise temperature, K**	50.0	50.0	50.0		5.0	5.0
(1-L) 290 K - Line loss raise temperature	31.0	60.0	100.0		20.0	100.0
Total system noise temperature K, at receiver input	481.0	510.0	800.0		420.0	1280.0
Noise density, η_T dBW/Hz	-201.8	-201.5	-199.6		-202.3	-197.5
P_r/η_T dB-Hz	47.8	51.0	G_u+50.6	G_u+44.6	EIRP+55.4	G_u+44.4

***For 26 degree conical coverage, 29.3 dBW for 30 degree coverage.**
****Adjusted for line loss.**

TABLE 5. TDRS RECEIVE LINK BUDGETS

Parameter	Return LDR VHF (Minimum)	Return Voice VHF	Return MDR S Band	Order Wire S Band	Forward LDR F[illegible] G[illegible] K[illegible]	Forward HDR, MDR From Ground Ku Band	Return HDR Ku Band
Transmit power	7.0	20 0		20 0		P	
Transmit antenna gain	-3.0	0	EIRP	[illegible]	[illegible]	62 0	EIRP
Transmit line loss					[illegible]5	-2.5	
Transmit pointing loss					0 5	-0.5	-0.5
Space loss	-167 5	-167 5	[illegible]92 7	[illegible]92 7	207.5	-207.5	-208.3
TDRS antenna gain	18.8*	19.5	36 2	[illegible]3 2	18.5	51.5	51.9
TDRS pointing loss	-	-	-0.5		-2.0	-0.5	-0.5
TDRS line loss, L	-1.0	-1.0	-0.8	-1.0	-1.0	-2.0	-2.0
TDRS ellipticity loss	-0.5	-0.2	-0.2	-0.2	0	0.2	-0.2
Receiver power, P_r	-146.2	-129.2	EIRP-158.0	-160.7	P-133	P-99.7	EIRP -159.8
Noise figure, dB	3.9	3.9	1.3	3.9	9.0	10.0	4.0
Receiver noise temperature, K	940***	420.0	100.0	420.0	1170	2600.0	440.0
Earth noise temperature, K**	150.0	150.0	240.0	240.0	240.0	195.0	195.0
(1-L) 290 K - line loss noise temperature, K	60.0	60.0	58.0	60.0	60.0	105.0	105.0
Total system noise temperature, K	1250.0	630.0	398	720.0	1470.0	2900.0	740.0
Noise density, η_T dBW/Hz	-197.6	-200.6	-202.6	-200.0	-196 9	194.0	-199.9
P_r/η_T dB-Hz	51.4	171.4	EIRP+44.6	39.3	P+63.9	P+94.3	EIRP +40.1

*For 30 degree conical coverage.
**Adjusted for line loss.
***RMS sum for five receivers.

3.1.1.5 S Band Transponder

- A turnaround S band transponder has been provided to allow accurate TDRS range measurements. The bandwidth is 8 MHz centered at 2029 for receive and 2210 for transmit. The transmitted EIRP is 20 dBW. This transponder will allow the use of trilateration techniques and is compatible with the Goddard range and range rate system. This transponder is also used for backup TT&C when used in conjunction with an omnidirectional antenna.

3.1.2 Link Parameters

The features, characteristics, and parameters associated with each link of each service are presented below.

3.1.2.1 Low Data Rate Service

Fo ward Link

The user commands and the voice signal are multiplexed in synchronous code division using different PN codes, but occupy the same frequency band of 400.5 to 401.5 MHz.

Command Channel. The user command channel will be time-shar d; that is, only one user can be commanded at a time. However, commands may be sent to many users within a period of 1 minute. All users will receive the TDRS transmitter RF signal; thus each command will have a prefix that will activate the command decoder of the intended user.

Other operational features include:

• Automatic user acquisition	User available for command sh tly after becoming visible
• Time-shared link	Requires synchronized sequencing of user commands
• Fixed timing	User receivers can be standardized; ground operations and equipment can be simplified
• Variable format	Number of bits and their significance in a user command can be different for every user if desired (i e., command format flexibility).
• Baseline bit rate	300 bps
• Probability of bit error	$P_e \leq 10^{-5}$
• PN code length	2048
• One code per bit	
• Chip rate	614.4 kchips/sec
• Biphase PSK IF carrier modulation	
• EIRP	See Table 6.

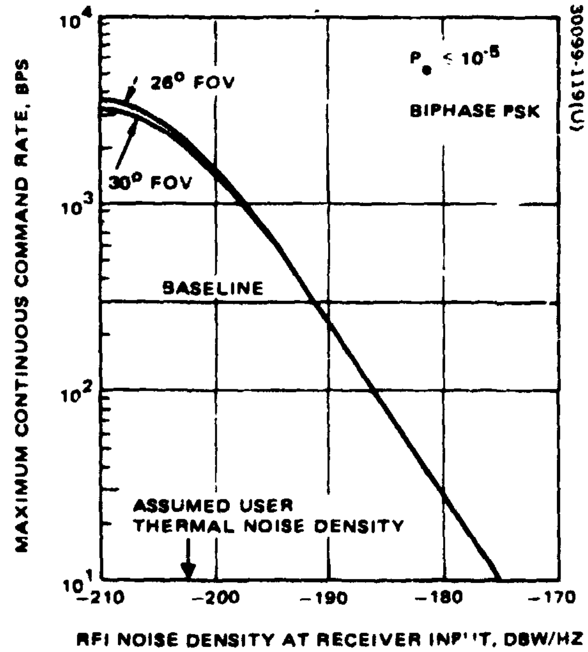


Figure 8. LDR Forward Link Command Rate

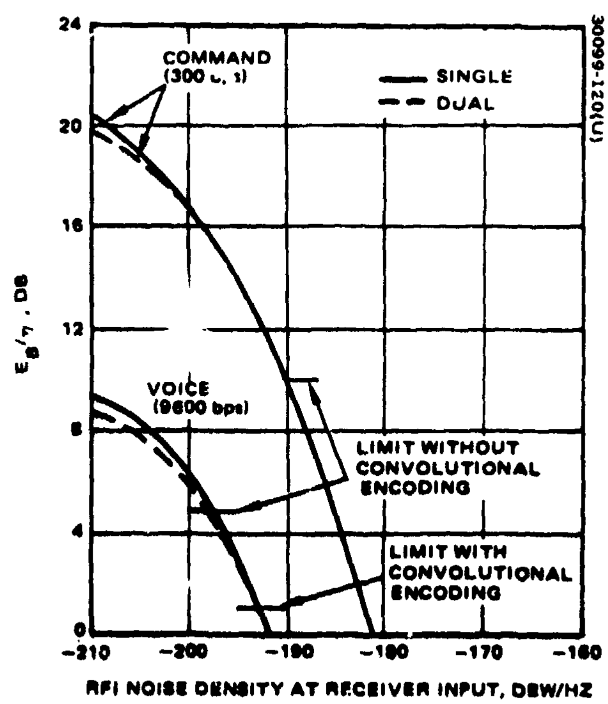


Figure 9. LDR Forward Link Bit Energy/Noise Density Ratio

TABLE 6. LDR FORWARD LINK EIRP

	26 Degree Field of View	30 Degree Field of View
Antenna gain, dB	12.5	11.8
Radiated Power, dBW	17.5	17.5
EIRP, dBW	30.0	29.3

Analysis of the low data rate links and a study of ground emitters have revealed that RFI is most likely the limiting factor in these links. Figure 8 shows how the bit rate is limited by RFI. The parameter chosen to quantify RFI is the average spectral density of the RFI power at the receiver input.

Voice Channel

- Analog-to-digital voice — 9.6 kbps delta modulation
- Rate one-half convolutional encoding
- PN code length — 32
- One PN code per convolutional code symbol
- Chip rate — 614.4 kchips/sec
- Biphase PSK IF carrier modulation
- EIRP — Same as command channel

The voice channel employs delta modulation to convert the analog voice signal to a binary waveform. The baseline bit rate is 9.6 Kbps; the bit energy-to-noise density is shown in Figure 9 as a function of RFI density. The use of convolutional encoding will allow operation at higher levels of RFI and will probably be required.

Return Link

The user telemetry and voice channels occupy separate frequency bands:

- Telemetry — 136 to 137 MHz
- Voice — 137 to 138 MHz

User Telemetry

Up to 20 users may simultaneously return telemetry. Code division multiplexing (CDM) will be used to allow simultaneous telemetry return. The PN codes for CDM will be different for each user spacecraft's telemetry. Convolutional encoding will be employed on user telemetry for bit error correction; link quality is improved significantly with this technique.

Baseline Signal Design

The baseline approach assumes that the return bit rate is standardized for all users but this is not a system requirement. With this standardization, the baseline parameters are as follows:

• Bit Rate:	1200 bps
• Probability of bit error	$P_e \leq 10^{-5}$
• Adaptive processing of all of the array antenna signals	
• Rate one-half convolutional encoding	
• One gold code per convolutional code symbol	
• Gold code length	512
• Chip rate	1.2288 Mchips/sec
• Biphase PSK carrier modulation	
• Estimated degradation due to ground link and processing (same as for the Part I TDRS)	3 dB
• Required E_b/η at decoder for $P_e = 10^{-5}$	4.1 dB-Hz
• User EIRP	≥4 dBW
• TDRS G/T per element (considering receiver generated noise only)	See Table 7.

TABLE 7. LDR RETURN LINK G/T

	26 Degree Field of View	30 Degree Field of View
VHF antenna element gain, dB	-12.7	12.0
Receiver noise figure, dB	3.9	3.9
Receiver noise temperature, K	420.0	420.0
Equipment G/T (at receiver), dB/K	-13.5	-14.2

The LDR return link bit rate per user is shown in Figure 10 as a function of the RFI power density at the TDRS receiver inputs. A performance range exists because the signal-to-interference ratio depends on the location of the user spacecraft with respect to the RFI pattern as seen by a TDRS. If the figure is correct, the baseline bit rate of 1200 bps from 20 users simultaneously is possible with an RFI noise density up to 180 dBw/Hz.

Figure 10 was the result of AGIPA analysis using a digital computer to simulate the RFI distribution and to compute the signal-to-noise ratio after ground processing as a function of total RFI level and user position. This analysis is discussed in Volume 2 of this final report.

Voice

The voice signal will be PN code modulated as required to meet CCIR requirements, but not to exceed a 1 MHz bandwidth.

- Analog-to-digital voice encoding — 19.2 kbps delta modulation
- Rate one-half convolutional encoding
- Biphase PSK carrier modulation

The signal spectrum can be located anywhere in 137 to 138 MHz. Minimum RF bandwidth is 60 kHz, but CCIR limits may require spreading. TDRS G/T is the same as for the telemetry channel

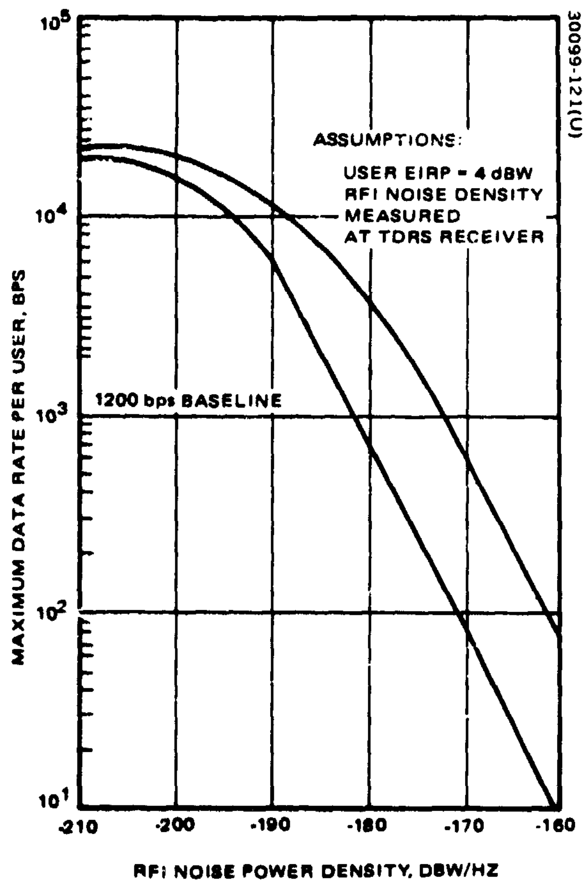


Figure 10. LDR Return Link Capability

Tracking

Due to the PN code signaling, user spacecraft receivers automatically acquire and synchronize to the signal transmitted from a TDRS. After the brief acquisition period, range and range rate measurements can be made. However, the user's transmitter must be turned on, and the return signal acquired at the ground station. A particular operational advantage of the signaling concepts used here is that both range and range measurements can be made simultaneously with telemetry reception, and no forward link commands are required.

Range measurement uncertainty is affected by system noise, of which RFI appears to be the most severe. Figure 11 shows the RMS uncertainty as a function of RFI noise density for both forward and return levels. The total RMS uncertainty is the sum of the two link contributions.

3.1.2.2 Medium Data Rate Service

Three independent two-way channels are provided via the three dual feed antennas. The power subsystem and ground link transmitter have been designed to support two of the links simultaneously with the required margin. The third MDR channel has been provided for the following reasons: 1) To simplify and standardize HDR user acquisition with the use of a forward MDR channel, 2) to increase MDR service reliability. The provision of the third MDR channel will allow return from three MDR users simultaneously under most ground link weather conditions. However, the third forward link transmitter will be used for HDR link acquisition or limited to MDR command in the low power mode. Each two-way link has the characteristics listed.

Forward Links

• Channel bandwidth	30 MHz
• Channel center frequency placeable by ground command 2038 to 2118 MHz with 1 MHz discrete steps	
• High power mode	
Antenna gain	36 dB
Radiated power	11 dBW
EIRP	47 dBW

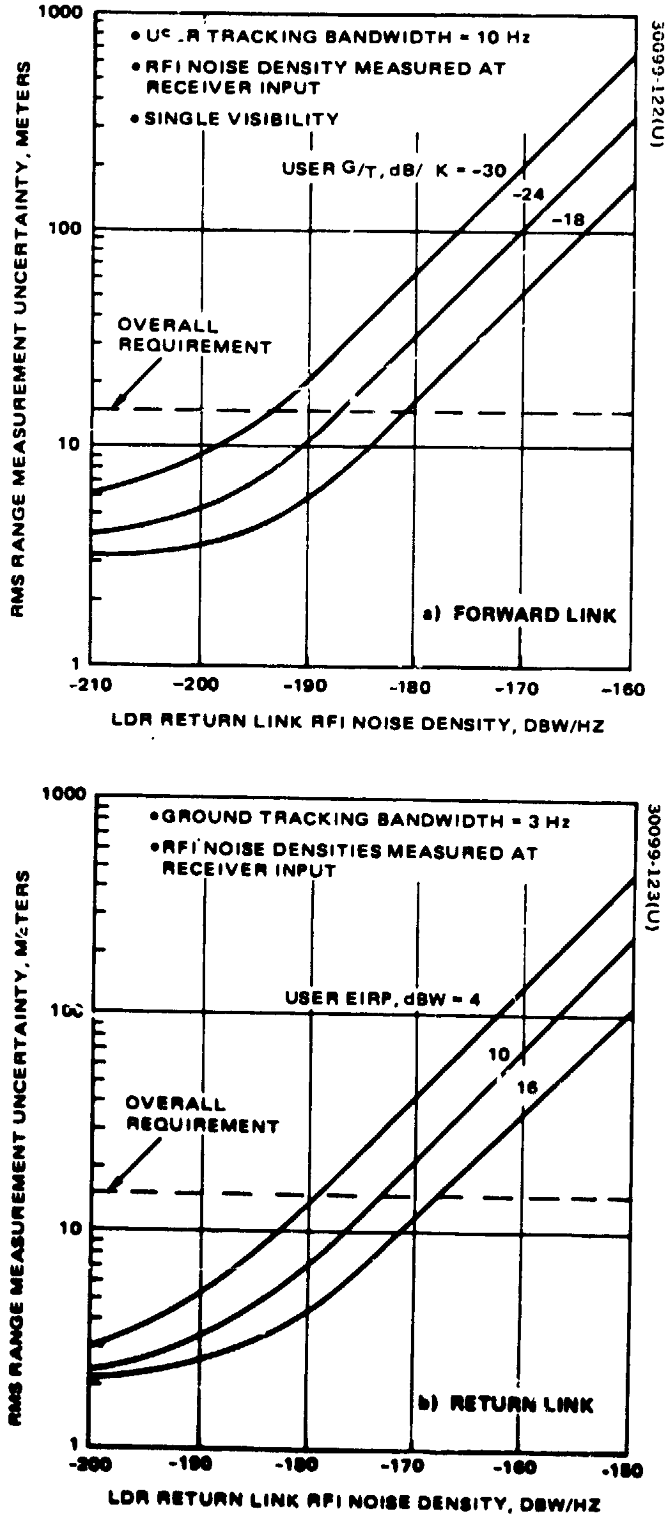


Figure 11. RMS Range Measurement Uncertainty

- Low power mode

Antenna gain	36 dB
Radiated power	5 dBW
EIRP	41 dBW

Figure 12 shows the maximum possible data rate that can be sent to an unmanned user assuming no error correction encoding, a receiver system noise temperature of 800 K, and 3 dB receive losses.

The link capacity for transmitting to the Space Shuttle is shown in Figure 13. The major assumptions of the link analysis accompany the figure. Note that the requirement for 54 kbps which includes two digital voice signals plus 2 kbps data can be accommodated with the high power mode.

Return Links

• Channel bandwidth	10 MHz
• Channel center placeable by ground command anywhere from 2220 to 2300 MHz band with 1 MHz discrete steps	
• G/T = 10. 2 dB/K at receiver input considering all noise sources	10. 2

The bandwidth of the return channels is smaller than that of the forward channels because the energy is radiated away from the earth most of the time. Consequently, the spectrum spreading required to reduce the earth-incident flux density to acceptable levels is less.

Figure 14 shows the relationship between the return data rate, radiated power, and antenna gain for an unmanned user. No link margin and no error correcting encoding have been assumed. Figure 15 shows the relationship between data rate, transmitter power, and antenna for the Space Shuttle. A number of assumptions have been made for this link as listed in the figure. The use of coding and the 10^{-4} bit error rate (BER) allows a bit energy to noise density of 5. 2 dB, whereas 10 dB was used in Figure 14. The assumed line loss plus margin tends to cancel the increase in link capacity due to coding relative to Figure 14. However, note that the requirement of 192 kbps can be achieved with a 40 watt transmitter and 3 dB gain antenna on the shuttle.

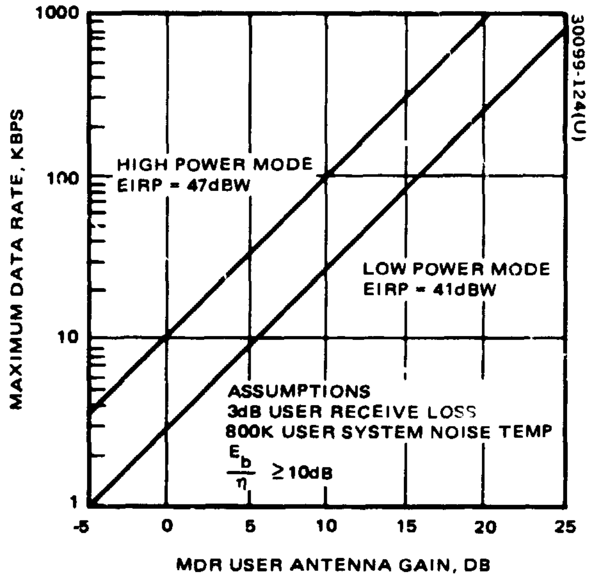


Figure 12. MDR Forward Link Capability for Unmanned User

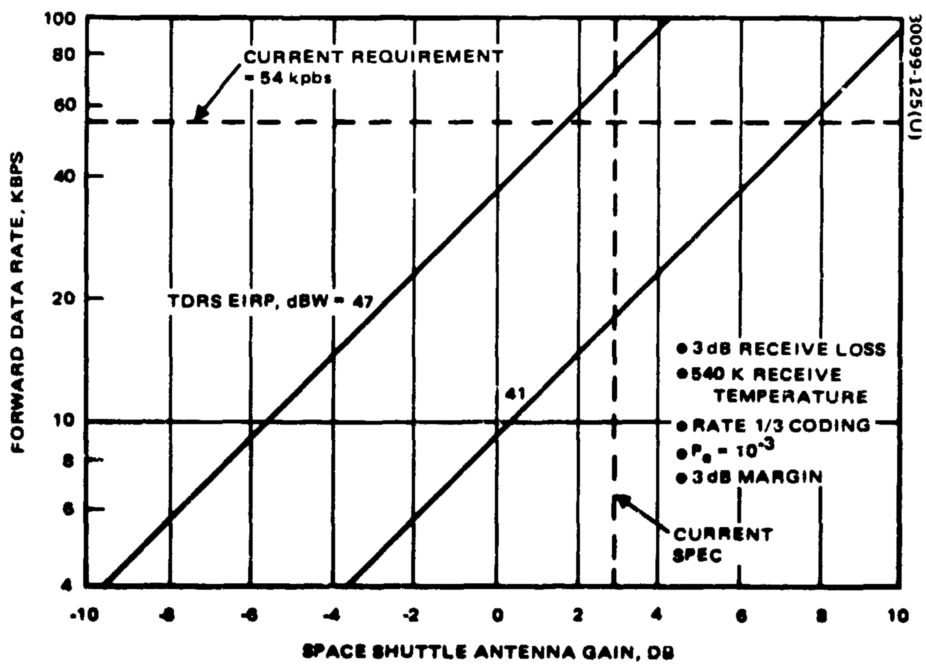


Figure 13. Space Shuttle Service Via TDRS Forward Command Plus Voice

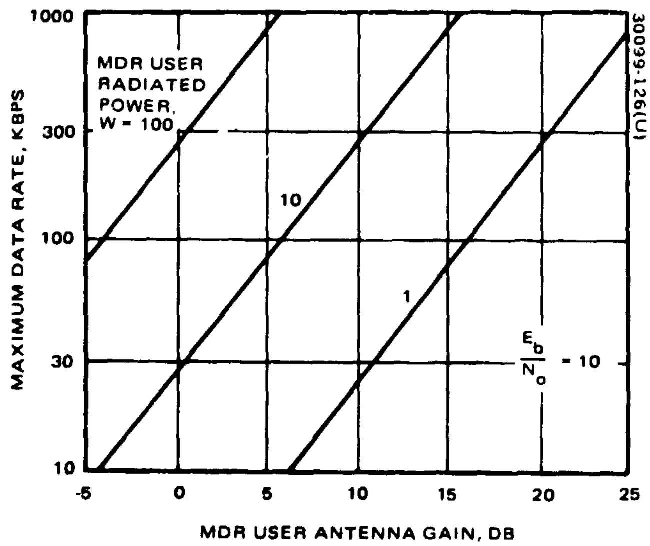


Figure 14. MDR Return Link Capability for Unmanned User

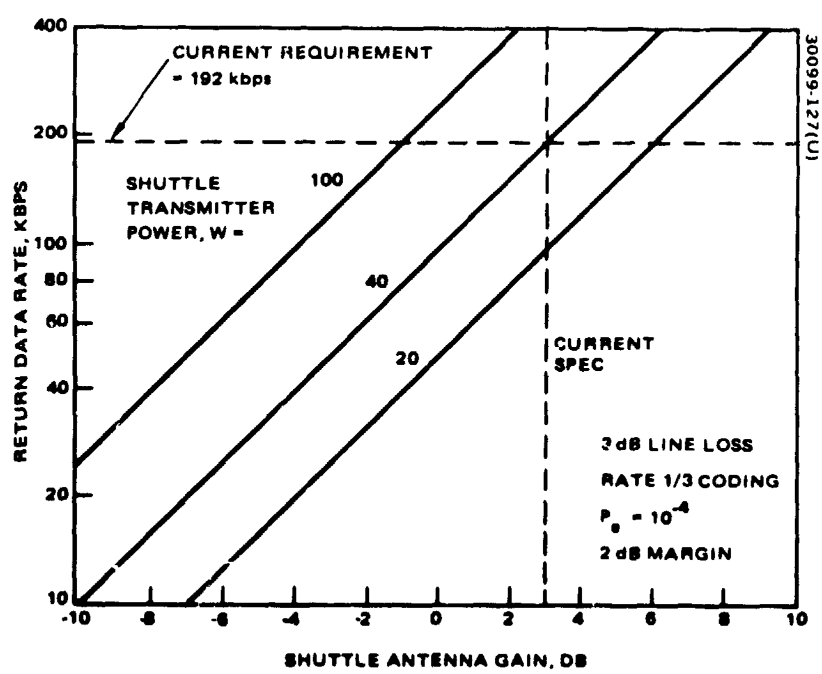


Figure 15. Space Shuttle Service Via TDRS Return Telemetry Plus Voice

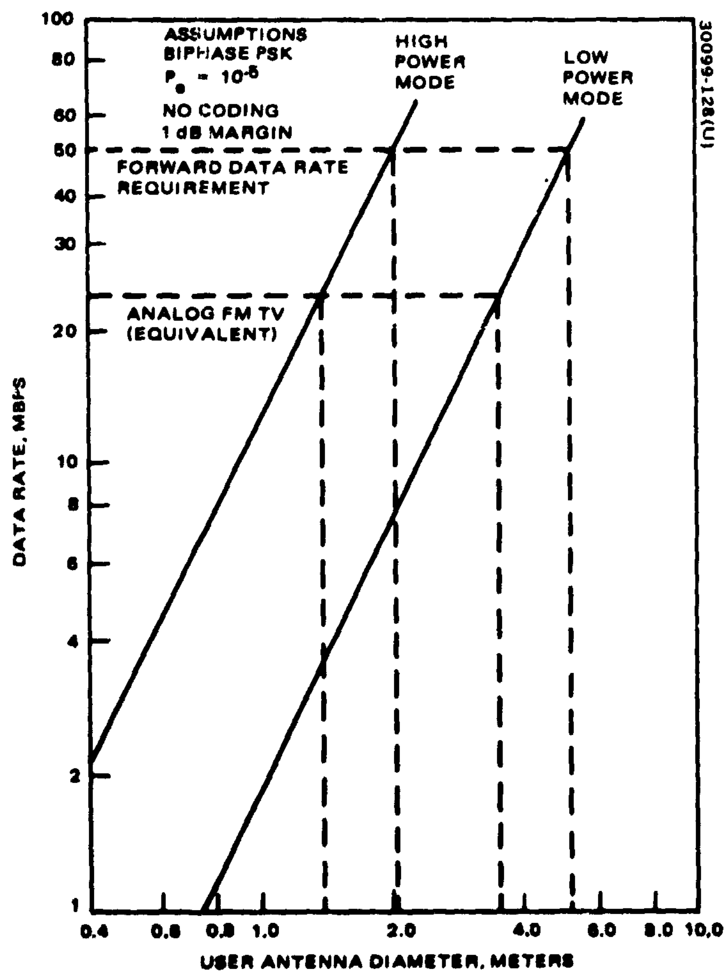


Figure 16. TDRS to HDR User (Forward Link)

3.1.2.3 High Data Rate Service

The HDR service provides two independent two-way channels. Any two of the three dual-feed antennas may be used for this service, but must also be shared with the MDR service. The TDRS/user link employs Ku band frequencies. If a user spacecraft has the capability, the dual feed and independence of the MDR and HDR repeater channels will allow a two-way link simultaneously at both S band and Ku band.

Forward Links

- TDRS to user frequency bands: — 14.760 to 14.810 GHz (50 MHz); 14.860 to 14.910 GHz (50 MHz)
- EIRP — See Table 8

Figure 16 shows the required user antenna diameter as a function of bit rate for the two power modes assuming a tunnel diode user receiver (7 dB noise figure).

Return Links

- Variable bandwidth — 100, 50, 10 MHz
- Center frequency of the TDRS/user links — 13.800 and 13.950 GHz
- G/T — 23.2 dB/K
- G — 51.9 dB
- T — 740 K including all noise sources

TABLE 8. HDR FORWARD LINK EIRP

	High Power Mode	Low Power Mode
Antenna gain, dB	52.8	52.8
Radiated power, dBW	6.2	-1.8
EIRP, dBW	59.0	51.0

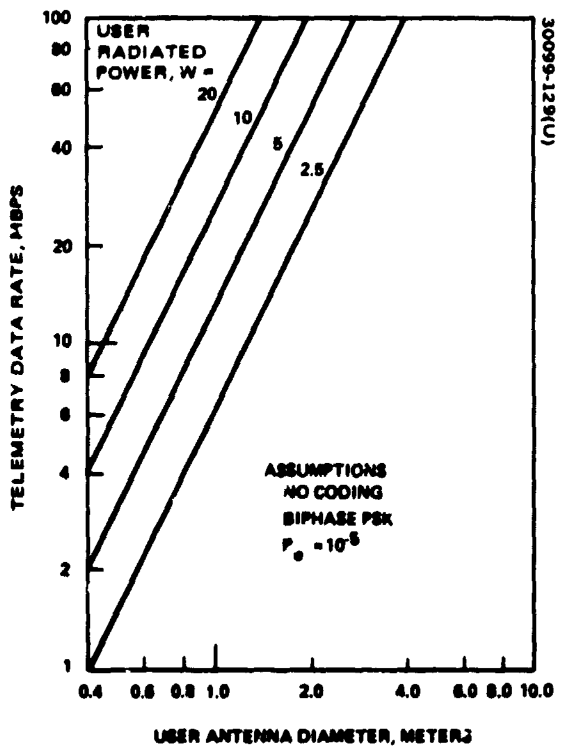


Figure 17. HDR Return Link

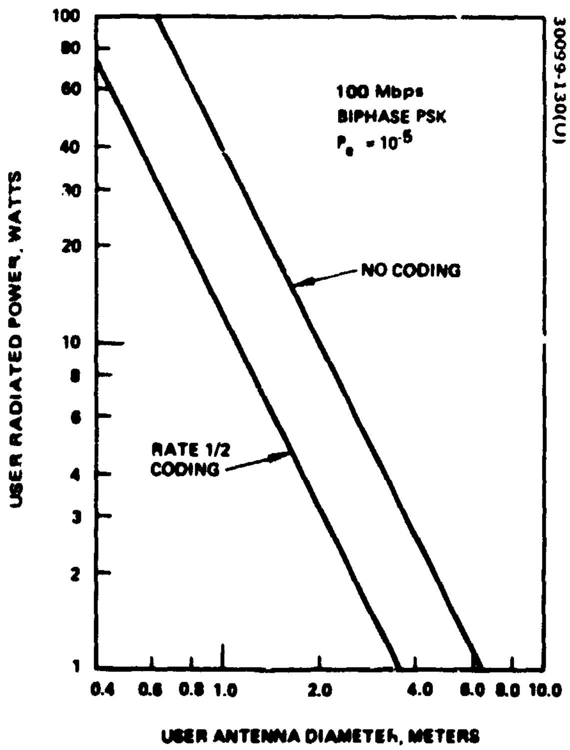


Figure 18. HDR User Requirements for 100 Mbps Telemetry

Figure 17 shows the relationship between the required user antenna size, radiated power and return data rate. Figure 18 shows the relationship between the required user antenna diameter and radiated power for a data rate of 100 Mbps with and without the use of error correcting encoding.

3.1.2.4 Order Wire Service

- Center Frequency — 2218 MHz
- Bandwidth — 1 MHz
- G/T -15.2 dB/K at receiver over 19.5 degree earthcentered cone considering all noise sources.

3.1.2.5 S Band Transponder

- Frequency band

Receive	2025 to 2033 MHz
Transmit	2206 to 2214 MHz

- EIRP

	Antenna gain = 13.5 dB
	Radiated power = 6.5 dB
	EIRP = 20.0 dBw

3.1.2.6 Ground Links

A weather margin of 17.5 dB has been provided for all channels in both the forward and return links between the TDRS and ground station.

Forward Link

A northern hemisphere coverage horn is used to receive the LDR, beacon, and TDRS command channels from the ground station. A 3.82 meter parabolic reflector antenna is used to receive the three MDR and two HDR channels.

The LDR channel, frequency reference beacon, the TDRS commands are received via northern hemisphere coverage horns.

• High gain antenna	G/T: 17.3 dB/K
G	51.9 dB
T	2900 K including all noise sources

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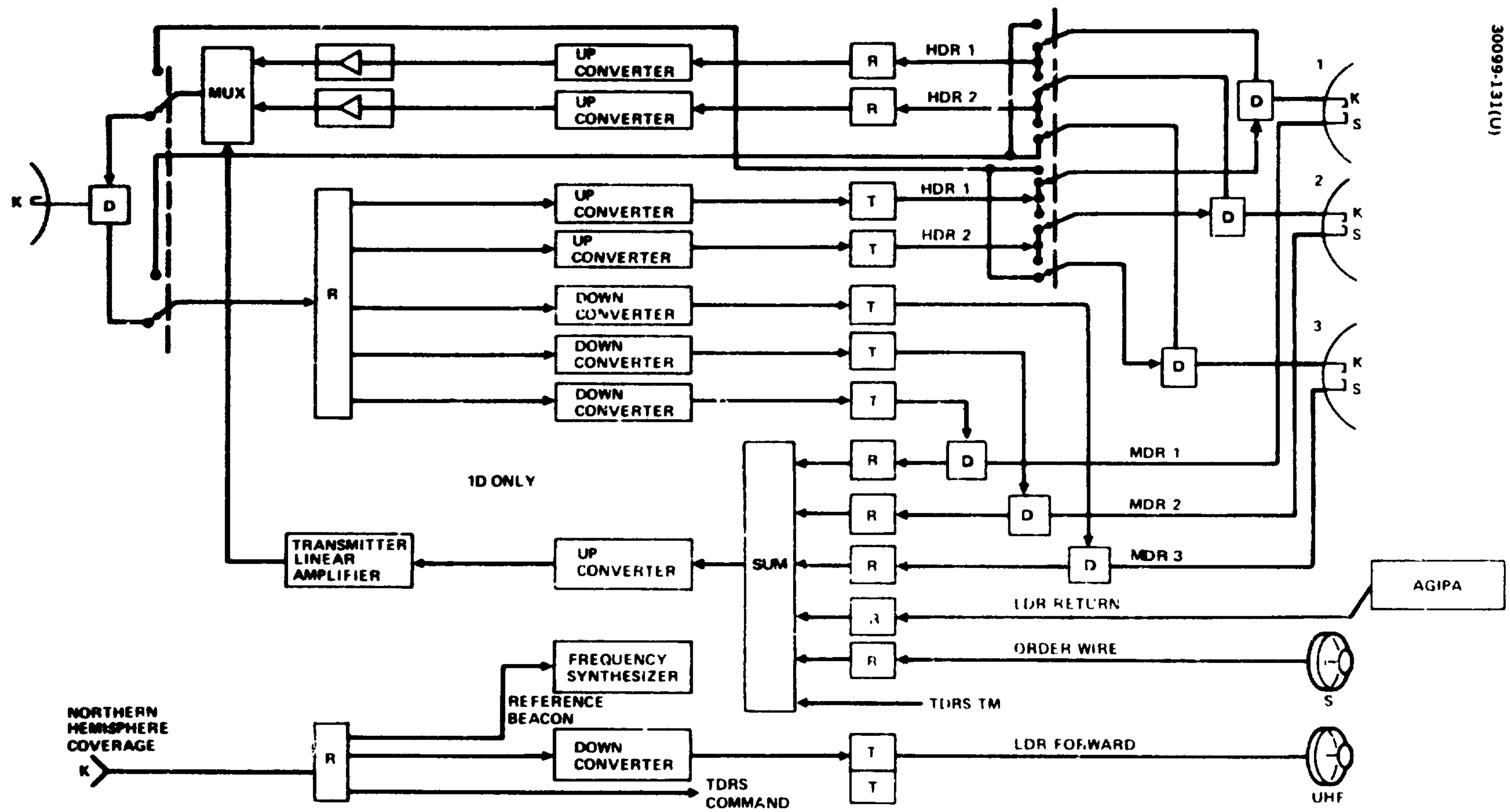


R = RECEIVER
T = TRANSMITTER
D = DIPLEXER

Figure 19. TDRS Repeater

- Low gain antenna — G/T: -13. 2 dB/K

  G — 18. 5 dB

  T — 1470 K including all noise sources

- The minimum carrier to noise power at the TDRS receiver in each channel is 15 dB.

- Frequency bands:

  13. 400 to 13. 420 GHz for the low gain antenna receiver

  13. 430 to 13. 700 GHz for the high gain antenna receiver

Return Link

There are three power amplifiers, the outputs of which are multiplexed and transmitted to the ground station via the 3. 82 meter Ku band antenna. Two of the power amplifiers contain the two HDR signals and operate in a saturated mode. The third power amplifier provides linear amplification required by the multiple signals and by the LDR adaptive processing. Major link characteristics are listed below. Bit energy-to-noise density for each signal is given in Table 9.

3. 2 TDRS REPEATER

Figure 19 is a simplified functional diagram of the repeater. The antennas on the left are for communication with the TDRS ground station and the antennas on the right are for communication with user spacecraft. The

TABLE 9. HDR RETURN LINK BIT ENERGY-TO-NOISE DENSITY

Return Service	Minimum Ground Link E_b/η, dB	Maximum Data Rate Per User, Kbps	Minimum Weather Margin, dB
Low rate data	14	1.2	17.5
LDR voice	14	20.0	17.5
Medium rate data	20	1,000.0	17.5
High data rate	15	100,000.0	17.5
TDRS telemetry	15	1.0	20.0
Order wire	15	1.0	20.0

forward LDR channel, TDRS commands, and frequency reference beacon are received from the ground station via a northern hemisphere coverage Ku band horn as shown in lower left of the figure. The LDR signal is upconverted and transmitted to users via the broad coverage UHF antenna. The command signal is sent to the TDRS decoder and the reference beacon to the frequency synthesizer to provide system coherency for all frequency conversions.

The three MDR and two HDR forward channels are received from the TDRS ground station via the 3.82 meter reflector antenna with the Ku band feed. The MDR channels are appropriately downconverted to S band and amplified for transmission. The HDR channels are upconverted from the receive Ku band frequencies to the transmit Ku band frequencies as shown in the frequency plan of Figure 7b.

The three return MDR channels, the ten return signals from the LDR VHF array antenna, the order wire channel and the TDRS telemetry are added together in frequency multiplex, upconverted to Ku band, and linearly amplified for transmission. Linear amplification is required to reduce intermodulation between channels and to allow adaptive processing at the ground station for up to 20 users simultaneously. The return HDR channels are upconverted from Ku band receive frequencies to Ku band transmit frequencies and amplified in saturated (i.e., limiting) amplifiers for power efficiency. The outputs of the three power amplifiers are multiplexed and the resultant diplexed with the incoming combined forward MDR and HDR band for transmission to the ground station via the 3.82 meter Ku band dish.

The switches associated with the ground link signals and the HDR signals provide redundancy that will allow only slightly reduced service if one of the large reflector antenna subsystems should fail (including positioner, feed, and tracking electronics). The 3.82 meter antenna at the left of Figure 19 has only a Ku band feed and is the initial and primary ground link antenna. If it should fail, however, either dual feed antenna 1 or 3 as shown in the figure may be used for the ground link. If, for instance, antenna 3 were used, then antennas 1 and 2 would be used for HDR channels 1 and 2, respectively, and would be time-shared with MDR service. Lost would be the capability to provide the third two-way MDR link simultaneously with two other links, either MDR or HDR or one of each. The ability to provide two backup antenna subsystems for the ground link greatly enhances the system reliability and long-life service potential.

If the primary ground link antenna operates as designed, then the switches allow both the HDR channels to be provided even if one of the dual feed antennas should fail.

The major antenna parameters are summarized in Table 10. More detailed discussion of the repeater is presented in subsection 4.3.1.

TABLE 10. TDRS ANTENNA PARAMETERS

Link	Antenna Frequency, MHz	Antenna Diameter, meters	Minimum Antenna Gain over FOV, dB
Low data rate forward	UHF	1.43	12.5
Low data rate return	VHF	3.82	18.5
Medium data rate forward	S band	3.82	35.5
Medium data rate return	S band		36.2
High data rate forward	Ku band	3.82	52.8
High data rate return	Ku band		51.9
Order wire	S band	0.267	13.1
TDRS/ground	Ku band	3.82	52.8
Ground/TDRS	Ku band	Horns	18.5

3.3 USER EQUIPMENT

3.3.1 LDR and MDR Users

Both low data rate and medium data rate users will require spread spectrum transceivers. The carrier signals are modulated by binary PN sequences (codes), which in turn have been modulated by data. The use of PN coding for spectrum spreading accomplishes four objectives:

1) Allows code division multiplexing

2) Reduces multipath interference

3) Reduces the earth incident flux density (to meet CCIR requirements)

4) Improves range measurement accuracy

All four of these reasons are important in the LDR system, and all but the first are important in the medium data rate system. The low data rate PN symbol (chip) rate is 614,400 chips/sec in the allocated 1 MHz (400.5 to 40.1 MHz) band. The forward link bandwidth of the medium data rate service is 30 MHz, and the signal must be spread over most or all of this band to minimize the flux density. Thus, the MDR signaling rate may be more than 30 times greater than that of the LDR system. However, the transceiver operation will be basically the same for both services. The user transceiver (receiving/transmitting equipment) consists of the following major components, inter-related as shown in Figure 20: receiver, command data correlator, telemetry modulator, transmitter, interface buffers, and a signal acquisition, and matched filter correlator.

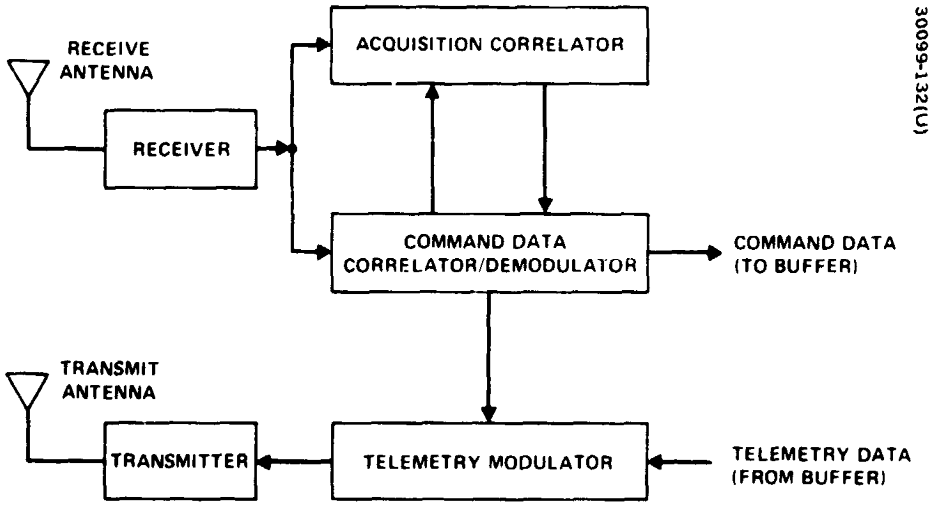


Figure 20. User Transceiver

The acquisition correlator permits rapid forward link signal acquisition and provides PN code timing to the command correlator, which maintains pattern and frequency lock after initial acquisition. The telemetry transmitter frequency may be phase locked to the received frequency for ranging, but may also be allowed to run free during telemetry data transmission enabling handover between TDRSs without interrupting data flow.

To operate with the TDRS system, a user spacecraft does not need to replace or modify its NASA ground station-compatible equipment, but must supplement it with the TDRS-compatible transceiver and antennas. Two types of standard transceivers are envisioned, one for LDR users and one for MDR users. These transceivers can be connected with a switch to the regular command decoder and telemetry encoder. The choice between the ground station or TDRSS operation could be made any time during the user's mission by a simple command of the switch setting. If the data and command rates for both modes of operation are different, an interface buffer unit will also be required as part of the transceiver package.

In addition to the standard transceiver, the LDR users will probably require a UHF antenna. The VHF link to the TDRS is compatible in frequency with the user to ground station link.

Figure 21 presents a more detailed transceiver description with numerical values corresponding to the baseline parameters of LDR forward command and return telemetry links.

For this implementation, the acquisition correlator gives the following performance when the bit energy-to-noise density, E_b/η at the receiver is 0 dB, which is 10 dB below the link design value:

Mean time to threshold (synchronous signal output)	0.1 second

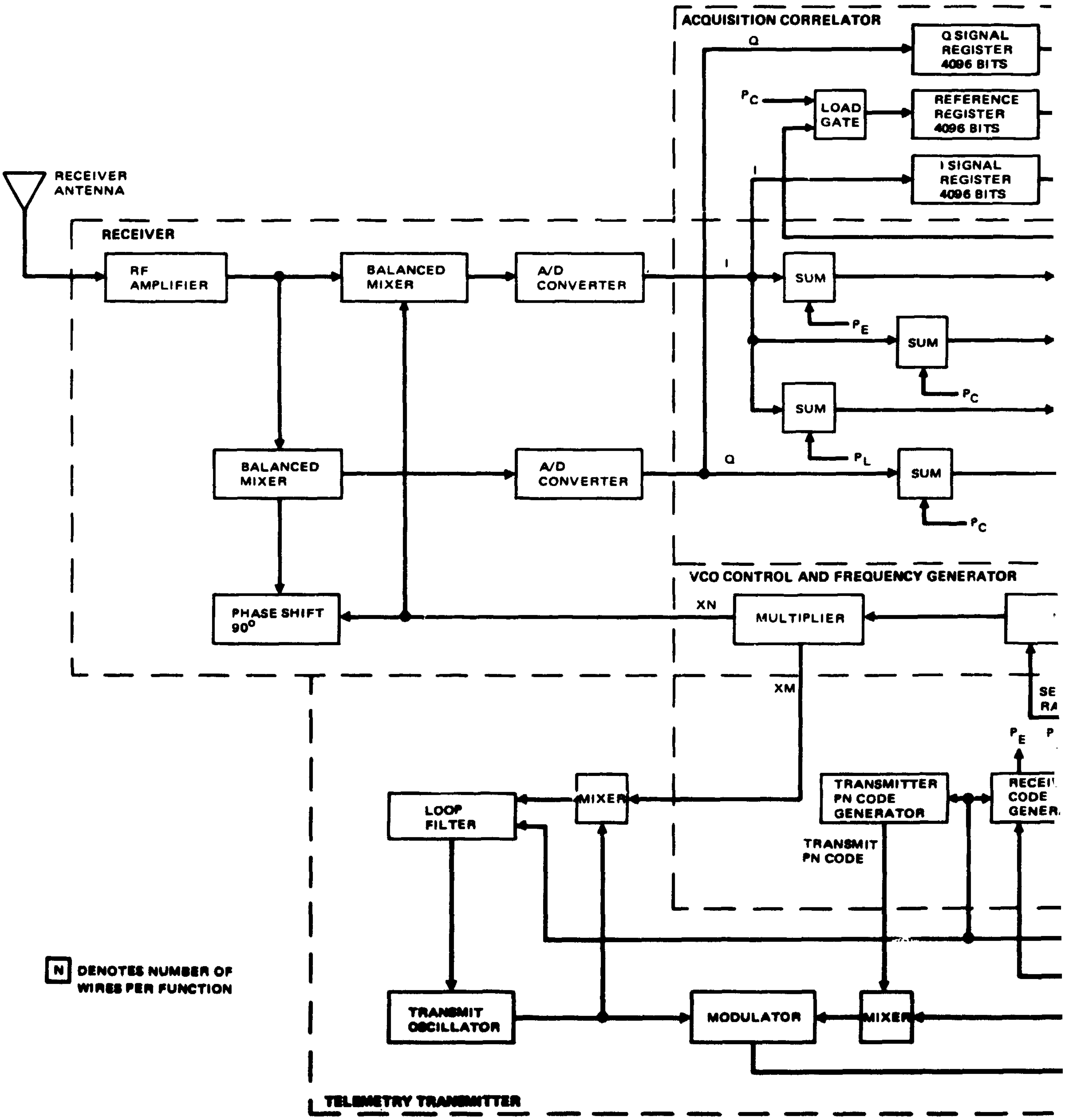
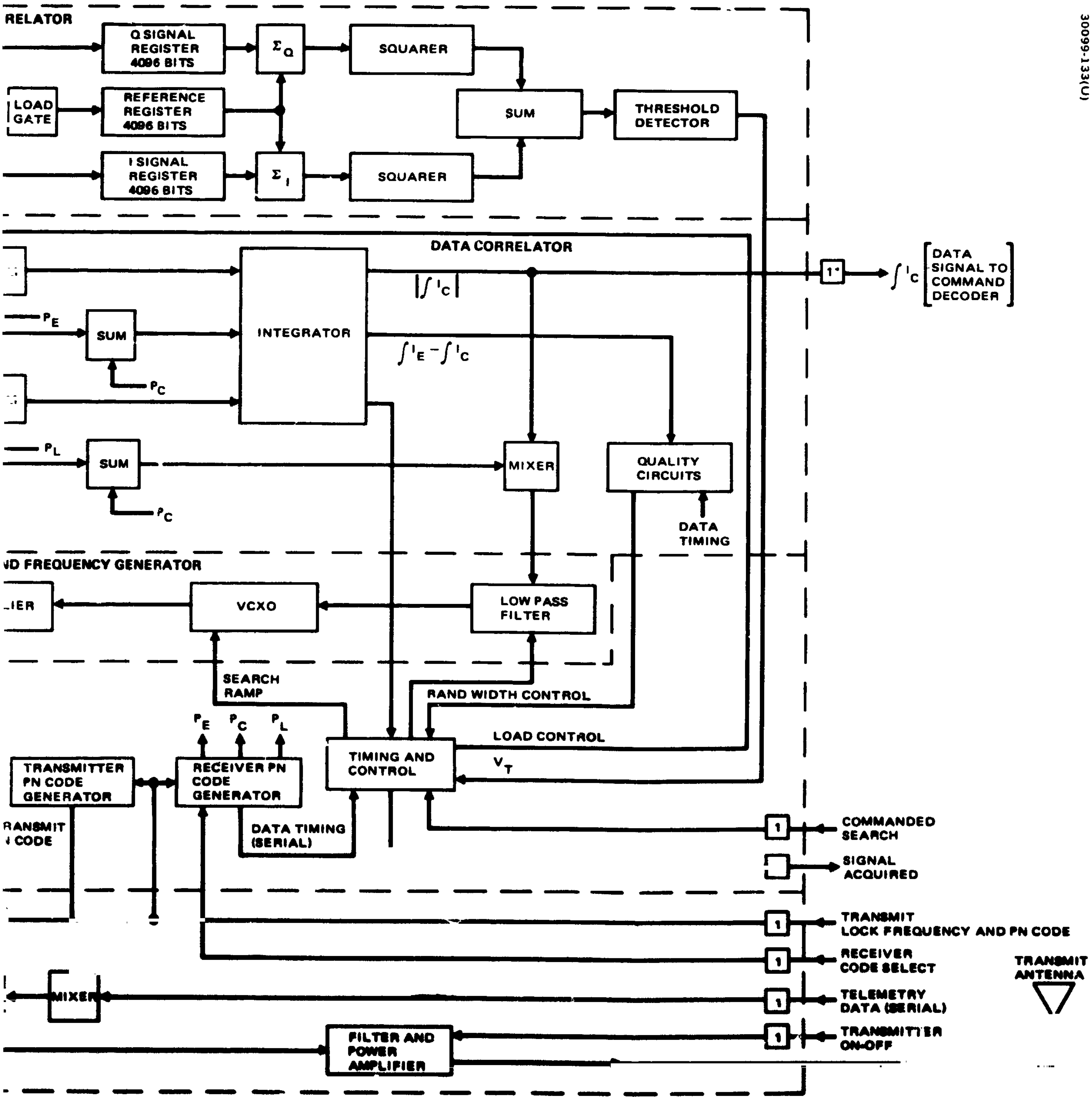


Figure 21. User Transceiver Detailed Diagram

FOLDOUT FRAME



FOLDOUT FRAME 2

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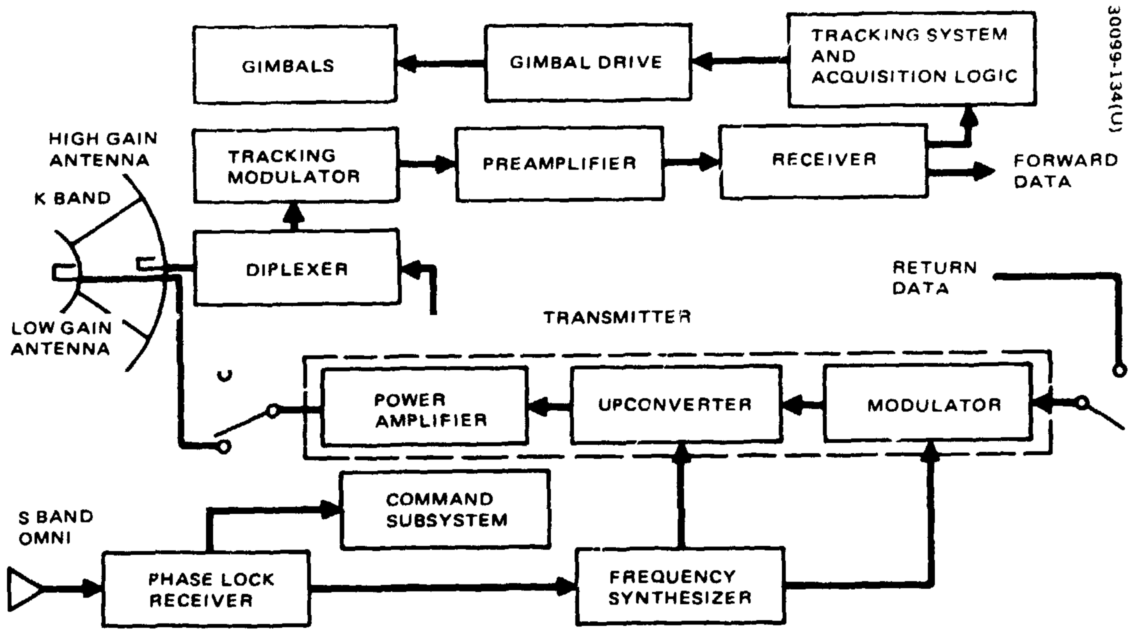


Figure 22. HDR User Communication Subsystem for TDRSS Operation

Probability of correct acquisition	0.99
Probability of a false synchronization output	0.01

In order for MDR users to realize the 1 Mbps capacity of the return link, a directive antenna will be required for expected transmitter power levels less than 30 watts. The relationship between user antenna gain and return data rate is shown in Figure 14. In order to allow communication during a major portion of the user's orbit, or whenever the user is visible to a TDRS, the directive antenna radiation must be steered. The most straightforward approach is to provide the capability to mechanically orient a single antenna structure; but whatever technique is employed, a steerable directive radiation pattern will be necessary for data rates near 1 Mbps.

3.3.2 HDR Users and Auto Tracking

Whereas the principal problem with the LDR and MDR links is code acquisition (i.e., signal synchronization), the principal problem of the HDR link is antenna beam acquisition and steering. The antenna half-power beamwidth will be less than 1 degree for most HDR users, necessitating special equipment for rapidly establishing the HDR user/TDRS link. A possible communication subsystem implementation is shown in Figure 22. The basic equipment required is as follows:

1) S band receiver with an omnidirectional antenna for command

2) Steerable, dual gain antenna

- Low gain; transmit only
- High gain; tracking feed, transmit, and receive

Preliminary user equipment characteristics are discussed in subsection 3. 3. 3.

The dual gain antenna shown in Figure 22 consists of two separate antennas and feeds rigidly connected to each other with parallel boresights. Only the high gain antenna has a tracking feed. With this equipment, the acquisition sequence is as follows.

1) The TDRS is commanded to point a dual feed antenna at the user with ±1 degree accuracy and an unmodulated carrier is transmitted at Ku band.

2) The TDRS transmits the following commands at S band which are received, verified, and executed via the user's S band omnidirectional antenna:

   - Point antenna at TDRS with ±3 degree accuracy
   - Switch power amplifier output to low gain antenna
   - Turn off carrier modulator
   - Turn on transmitter

3) The TDRS performs a spatial scan acquisition of the user carrier.

4) The user is commanded via S band to perform a scan acquisition of the TDRS signal (see step 1).

5) Following acquisition, the autotrack system is automatically activated, the user switches its transmitter to the high gain antenna, and data transmission begins.

In Figure 22, an output of the S band receiver provides a reference for the user's frequency synthesizer. This is not required, but if a frequency reference properly adjusted on the ground based on ephemerides is sent to the user, the effect of doppler shift can be compensated and the acquisition time can be reduced.

The maximum time required to perform steps 3 through 5 above is estimated to be 45 seconds. The antenna slewing of steps 1 and 2 will probably require more time. For instance, with the TDRS antenna slew rate of approximately 1 degree per second, slewing across the earth disc will require approximately 20 seconds. The user may be required to slew

180 degrees which would take 120 to 240 seconds, depending on positioner capability. However, this delay could be eliminated by prepositioning the antenna for the next communication period at the end of the current period.

3.3.3 User Telecommunication Equipment

User transponder equipment may be constructed using design approaches described for the TDRS repeaters. The principal difference in the detailed design is that the user equipment must operate in the complimentary transmit and receive bands. Minimum mass designs are required to minimize the impact on user satellites. The power consumption of power amplifiers and transceiver equipment must also be minimized by using high efficiency components in their design and construction. Complete redundancy in all electronic equipment is included. Equipment mass and power parameters are summarized in Table 11.

Low data rate transceiver equipment is implemented with microwave integrated circuit construction. The receivers utilize a transistor preamplifier to achieve a moderate noise figure as RFI will generally limit the command link performance. Transmitters feature high efficiency transistor power amplifiers developing 5 watts of output power. Overall efficiency of the transmitter is estimated to be 50 percent. An omnidirectional whip array antenna may be used on satellites using the Low Data Rate Service. Pseudo noise correlators are constructed with integrated circuits to minimize equipment mass and production cost. A crystal oscillator is provided for equipment operation prior to acquisition of the TDRS carrier which then provides the frequency reference for the transponder.

Medium data rate transceiver equipment at S band is also implemented with microwave integrated circuit construction. Command receivers for unmanned users utilize a transistor preamplifier to achieve a moderate noise figure. Higher data rates required for manned users are achieved by using a low noise parametric preamplifier and by operating the TDRS in the high power mode. A 5 watt transmitter is provided for unmanned user satellites. The required link performance of 1 Mbps may be achieved with a 5 watt transmitter and directional antenna with approximately 20 dB gain. The directional antenna is controlled by commands received through an omnidirectional antenna. A mechanical positioner with stepper motor drive is used to position the antenna. Applications requiring lower data rates may be implemented with an array of antennas which are switched to achieve beam steering. Beams are broad and can be controlled by computer generated ground commands. The MDR transceiver is also compatible with ground based satellite control and data acquisition facilities. Pseudo noise equipment is provided. It is implemented with integrated circuit construction.

The high data rate user equipment consists of a Ku band transmitter, a Ku band tracking receiver, a Ku band directional antenna and Ku band transceiver equipment for initial acquisition and contact with ground stations directly. The Ku band transmitter utilizes a TWT amplifier and a receiver implemented with waveguide circuitry. For a data link operating at 100 Mbps, an eight watt transmitter operating into a 2 meter antenna is

TABLE 11. USER TELECOMMUNICATION EQUIPMENT

Item	Number	Mass, kilograms	Power, watts
LDR User VHF/UHF		5.8	15.0
Receiver	2	1.0	1.0
Telemetry transmitter*	2	2.0	10.0
VCO control and frequency generator	2	0.3	1.0
Acquisition and data correlator	2	1.0	3.0
Antennas	1 Set	1.5	–
MDR User (1 Mbps) S Band		14.9	32.0
Command receiver	2	0.8	1.0
Telemetry transmitter*	2	2.7	20.0
Frequency synthesizer	2	0.3	1.0
Signal processor	2	1.0	3.0
Diplexer	1	1.7	–
Antenna, omnidirectional	1	1.0	–
Antenna, directional	1	1.4	–
Gimbal	1	4.2	–
Gimbal driver	2	1.8	6.0
HDR User (100 Mbps) Ku Band		27.2	62.3
Command receiver, S Band	2	0.8	1.0
Telemetry transmitter, S Band	2	2.7	(20.0)
Tracking receiver, Ku Band	2	5.1	5.8
Telemetry transmitter,** Ku Band	2	5.2	45.5
Frequency synthesizer	2	0.5	1.0
Signal processor	2	1.0	3.0
Diplexer, S Band	1	1.7	–
Diplexer, Ku Band	1	0.2	–
Antennas, S Band	1	1.0	–
Antennas, Ku Band	1	3.0	–
Gimbal	1	4.2	–
Gimbal driver	2	1.8	6.0

*5 watts RF power.

**12 watts RF power.

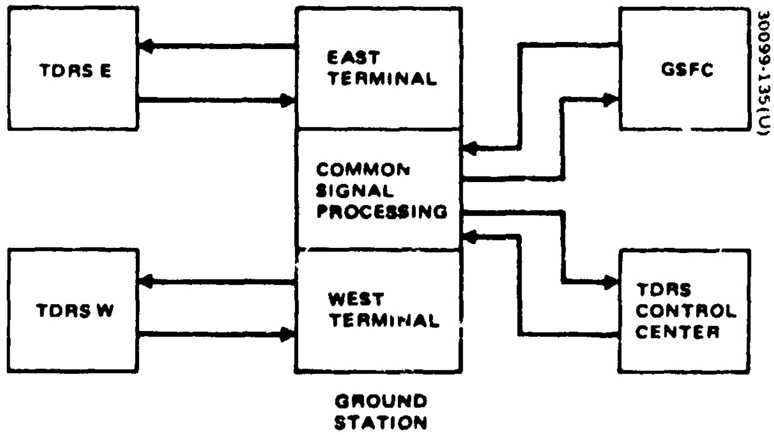


Figure 23. Overall Ground Station Concept and External Interfaces

required. As the beam width is less than one degree, autotracking is employed after acquisition of the link is achieved. The antenna is positioned with a mechanical motor employing a stepper motor driver.

3.4 TDRS GROUND STATION

The TDRS ground station is the interface element between the TDRSs and the two control centers – GSFC and the TDRS control center. The general relationship of the ground station to the other elements is shown in Figure 23. Also shown in the figure are three major portions of the basic ground station: 1) a terminal for maintaining RF communication with TDRS E, 2) a terminal for maintaining RF communication with TDRS W, and 3) a common area containing demodulation and processing equipment, which will be applied to signals from both terminals.

The RF terminals are of conventional design, but the signal demodulation and processing equipment, although not new in concept, has not been previously applied in the complexity required for simultaneous multiple user communication via the TDRSS.

It should be mentioned that a third terminal may be required for communication with the in-orbit spare TDRS and for redundancy. This will require only a slight increase in the processing equipment and its configuration controls.

The terminals consist of five major portions:

1) Antenna structure

2) Antenna tracking subsystem

3) Ku band RF/IF subsystem

4) VHF backup system

5) UHF antenna for TDRS tracking

The signal processing can be functionally separated into 15 functions:

1) LDR user telemetry demodulation

2) LDR voice demodulation

3) MDR channel 1 telemetry demodulation

4) MDR channel 2 telemetry demodulation

5) MDR channel 3 telemetry demodulation

6) HDR channel 1 telemetry demodulation

7) HDR channel 2 telemetry demodulation

8) LDR forward link modulation

9) MDR channel 1 forward link modulation

10) MDR channel 2 forward link modulation

11) MDR channel 3 forward link modulation

12) HDR channel 1 forward link modulation

13) HDR channel 2 forward link modulation

14) TDRS telemetry, tracking, and command

15) User range and range rate measurements

3.4.1 Ground Terminal Design

The equipment and associated parameters for a terminal are listed below.

3.4.1.1 Antennas

- Ku band/S band antenna
    1) Reflector diameter, 12.8 meter (42 feet)
    2) Ku band cassegrain feed
    3) S band near-focus feed

4) Polarization

a) Ku band, circular, C/CC

b) S band, circular, C/CC

5) Gain

a) 13.5 GHz, 62 dB

b) 15.0 GHz, 63 dB

c) 2040 MHz, 46 dB

d) 2220 MHz, 47 dB

6) Pedestal type: Azimuth/elevation

7) Autotrack system: single RF channel amplitude comparison, monopulse type

- UHF antenna for TDRS tracking

1) Frequency, 400.5 to 401.5 MHz

2) Gain, 5 dB

3.4.1.2 <u>Receivers</u>

- Ku band receiver

1) Location, rear of reflector

2) Noise figure, 3.9 dB

- S band receiver

1) Location, within terminal structure

2) Noise figure, less than 4 dB

- UHF receiver

1) Location, within terminal structure

2) Noise figure, less than 4 dB

3.4.1.3 Power Amplifiers

- Two 2 kW klystrons operational and two in standby
- The two HDR signals and three MDR signals are amplified in one power amplifier; the LDR, TDRS command, and beacon are amplified in the other.
- Power output allocations at the Ku band antenna feed:

  LDR: 1 kW

  MDR: 70 watts per channel

  HDR: 100 watts per channel

  Beacon: 20 watts

  TDRS command: 20 watts

Figure 24 shows the forward link RF/IF equipment and power amplifier arrangement.

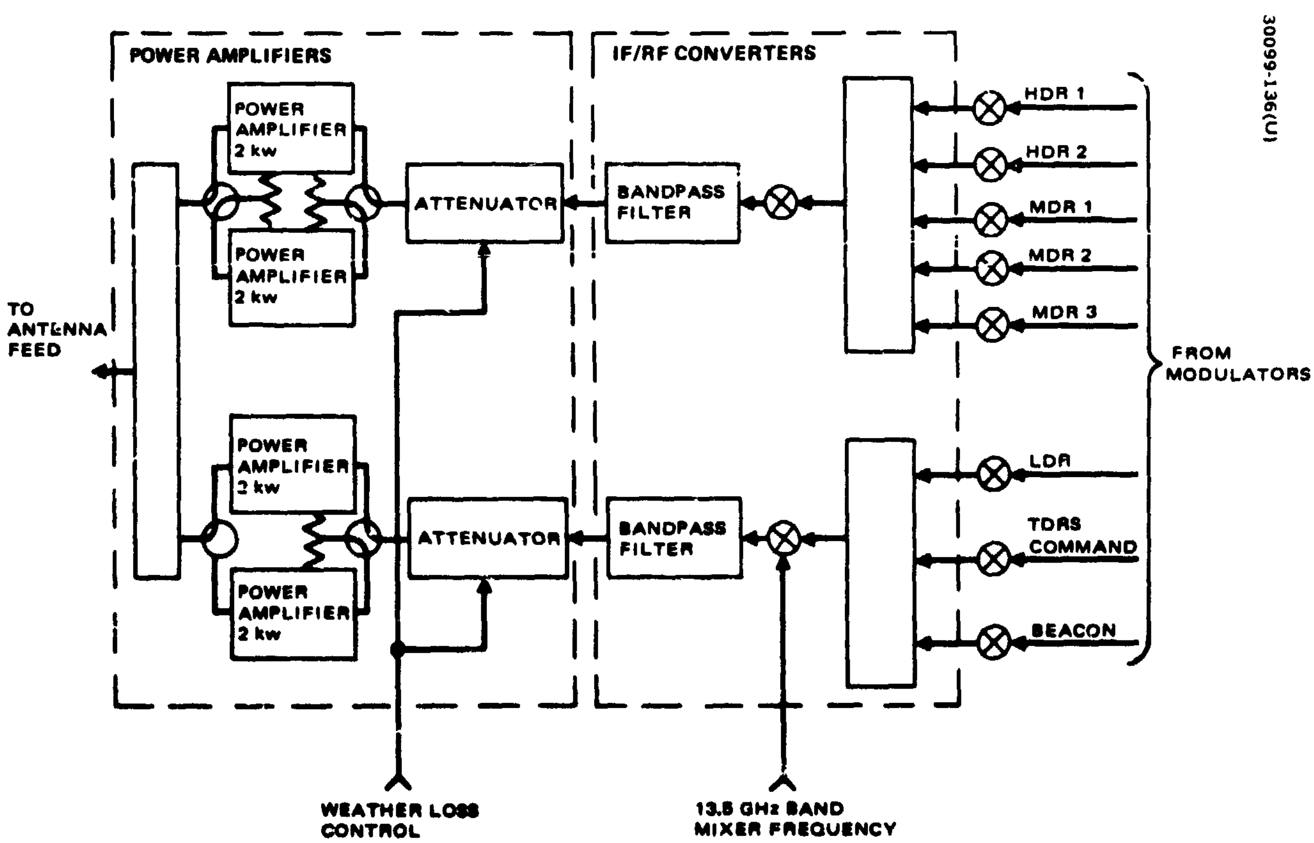


Figure 24. Power Amplifier and RF/IF Configuration

3.4.2 Signal Processing

The ground station return signal processing equipment must separate the individual channels in the two signals from each terminal, demodulate the data signals, and then multiplex all data for transmission to the GSFC telecommunication control center. These functions are illustrated in Figure 25 where for simplicity range and range rate measurements have been made part of the general demodulation process. The forward signal processing as shown in Figure 26 includes demultiplexing the signals from GSFC, modulating the LDR and MDR with PN codes, IF carrier modulation of all signals, and transmission to the two terminals. The voice must be switched to the correct LDR or MDR channel as directed from GSFC.

The major task required for the signal processing equipment is one of integration, control, checkout, maintenance, and replacement provision. All equipment, except the LDR return channel demultiplexing and demodulation equipment, is conceptually conventional. The equipment and major parameters follow:

3.4.2.1 Forward Links

- LDR telemetry PN/PSK modulator
  1) Quantity, 2
  2) Rate, 614.4 kchips/sec
- LDR voice PN/PSK modulator
  1) Quantity, 2
  2) Rate, 614.4 kchips/sec
- MDR PN/PSK modulator
  1) Quantity, 6
  2) Rate, 10 Mchips/sec
- HDR PSK modulator
  1) Quantity, 4
  2) Rate, 50 Mbps
- TDRS command
  1) Quantity, 2
  2) Type, three tone GSFC AM-FSK
  3) Bit rate, 128 bps

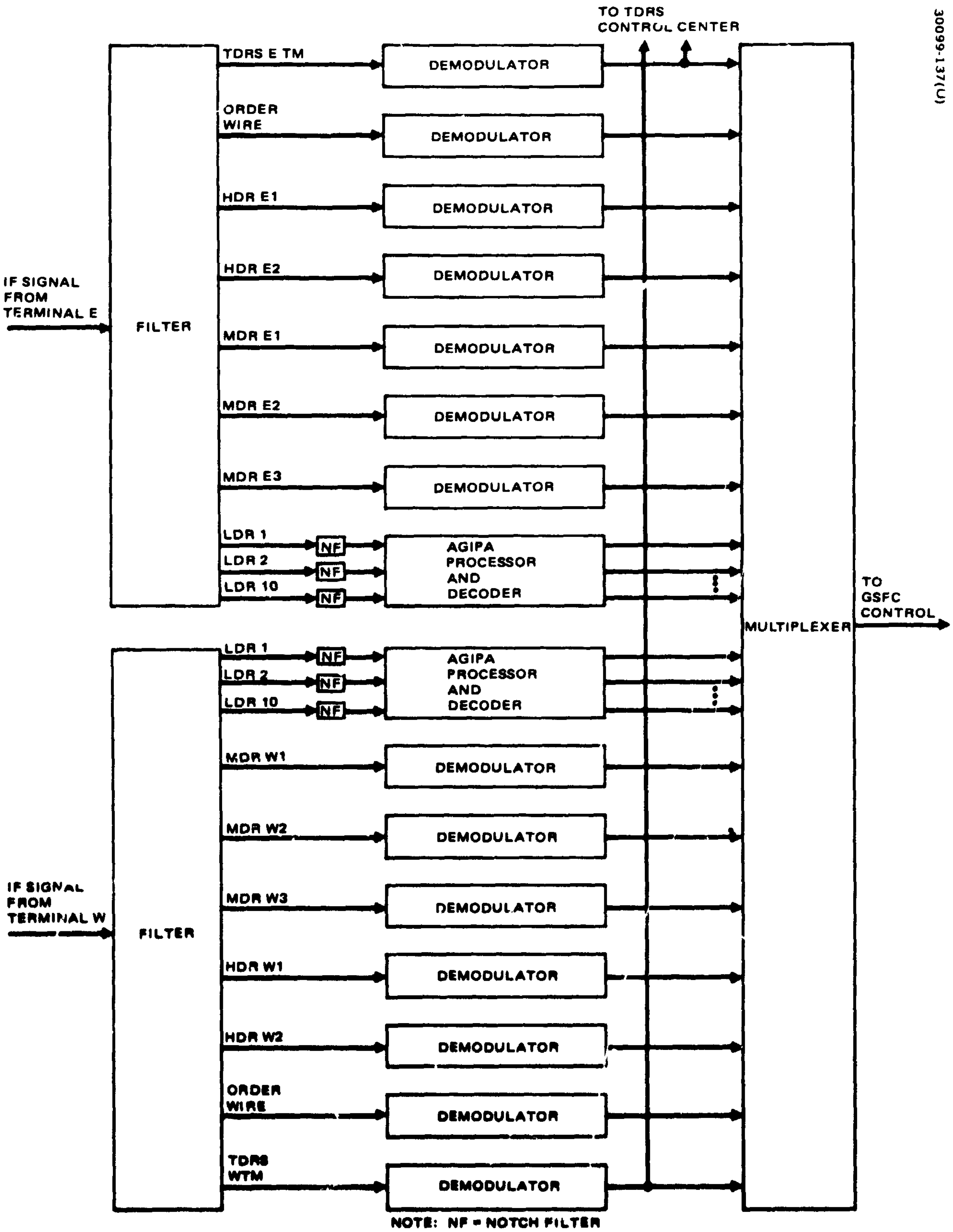


Figure 25. Ground Station Return Signal Processing

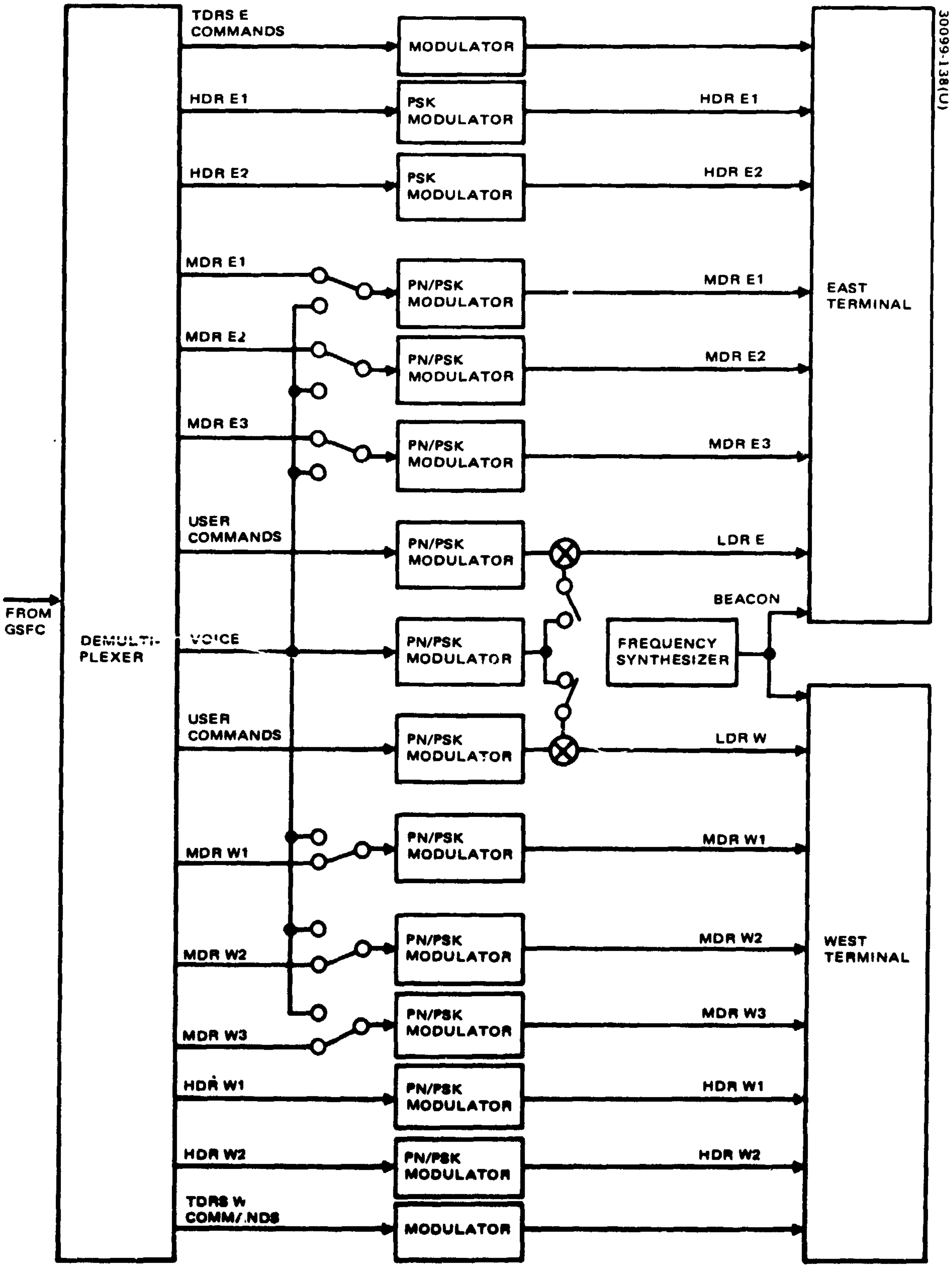


Figure 26. Ground Station Forward Signal Processing

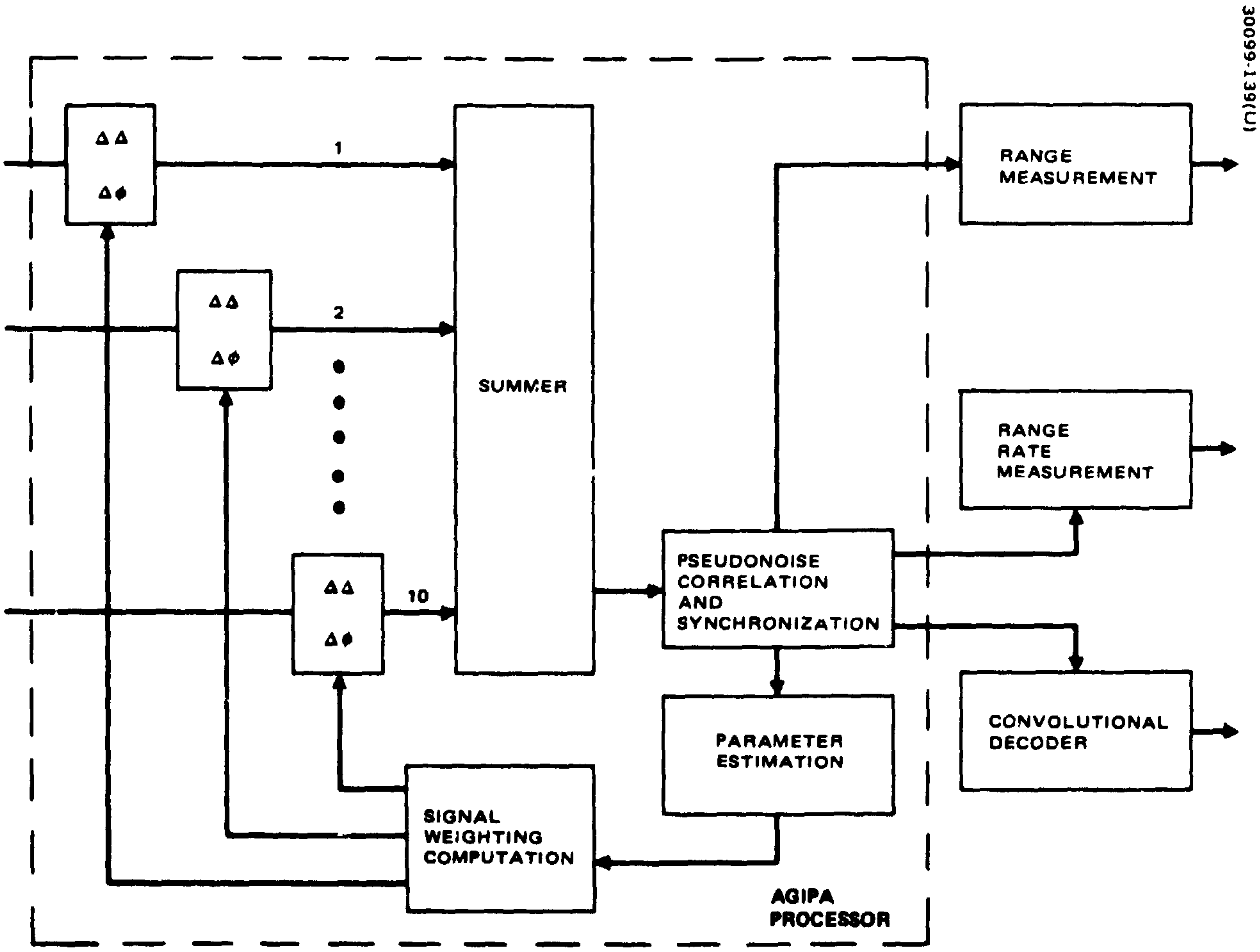


Figure 27. LDR Signal Processing

3.4.2.2 Return Links

- LDR telemetry – Notch filters will be used at IF in each LDR component signal as necessary to reduce high power, narrow-band interference (See Figure 23). For each user the following equipment is required:

    1) One AGIPA processor

    2) One convolutional decoder

    3) One range measurement unit

    4) One range rate measurement unit

The AGIPA processor includes the PN correlation process. A functional arrangement of the above equipment is illustrated in Figure 27.

- LDR voice – the ten component LDR signals containing telemetry also contain voice. The following equipment is required:

    1) One AGIPA processor

    2) One convolutional decoder – output bit rate 19.2 bps

- MDR – Biphase PSK correlation receivers must be used to demodulate to the return signals and produce output bit streams corresponding to the current user spacecraft telemetry rates; a standardized but variable bit rate device is envisioned.

- HDR – Two quadriphase PSK demodulators are required for the two links; the bit rate will depend on user requirements, but rates up to 100 Mbps are possible. Quadriphase is required for bit rates exceeding 50 Mbps because of the 100 MHz bandwidth limit, but biphase PSK modulation/demodulation may be used for bit rates less than 50 Mbps.

4. TDR SPACECRAFT DESIGN

4.1 DESIGN CONCEPT

The TDR spacecraft is designed to provide command and data relay capability for low, medium, and high data rate unmanned user spacecraft and voice, command, and data relay capabilities for manned user spacecraft. All transmissions from the TDRS ground station are at Ku band. In the spacecraft repeater a frequency translation is performed prior to transmission to the various users. Low data rate (LDR) user commands are frequency translated to UHF for transmission to the user satellites. The UHF forward link channels utilize broad beam antennas oriented toward earth center. An independent voice channel is also provided in this frequency band. Medium data rate (MDR) user commands are frequency translated to S band for transmission, and high data rate (HDR) user commands and data are frequency translated to the Ku band frequencies.

For the MDR and HDR service three dual S/Ku band feed 3.82 meter (12.5 foot) diameter paraboloid reflector antennas are provided. These antennas are time-shared between the MDR and HDR service. Switching circuitry is provided so that each antenna may be used for either service.

Three S band channels and two Ku band channels are implemented in the TDRS repeater. Only two of the three S band channels at a time are required for the MDR service; thus the third channel provides additional redundancy.

The LDR and MDR data and voice return links are provided at VHF and S band, respectively. A broad beam return link is also provided at S band to provide an emergency order wire service for manned users. The VHF, LDR return is designed with a five-element AGIPA. Both horizontal and vertical polarization of the return signal from each antenna element is transmitted to the ground in an independent channel, where it is processed to maximize the signal/interference ratio of the return beam.

The HDR return links are implemented at Ku band. The links from the TDRS to the ground station are also at Ku band and are implemented with a narrow beam antenna.

The TT&C subsystem uses the Ku band links for primary operations. An S band transponder provides a backup capability in the event that contact cannot be made with the TDRS with the Ku band links. The S band transponder is also used for trilateration tracking of the TDRS. The command subsystem uses the 128 bps PCM-FSK/AM format to send the commands. A real time execute capability is desirable to simplify equipment. This requirement is met by providing an execute tone at a different frequency than the 0 and 1 tones employed in the command signals.

Pointing of the high gain S band antennas is accomplished by ground command. In this case of the S band antenna with a beamwidth of approximately 2.5 degrees, open loop pointing with an accuracy of the order 0.5 degree is feasible. The Ku band antennas with a beamwidth of approximately 0.35 degree require an autotrack capability. Acquisition is accomplished for those antennas equiped with dual S/Ku band feeds by initially making contact with a user at S band and then going through a search at the user satellite for a broadened Ku band beacon signal transmitted by the TDRS. After the user has acquired the TDRS, the TDRS then searches and locks into the Ku band transmission from the user.

Attitude control requirements are to provide a stable platform for antenna pointing. It is not essential to control the despun platform orientation to less than 0.5 degree, but it is necessary to measure the orientation of the spin vector and the despun platform azimuth to an accuracy of the order of 0.1 degree. Thus short-term dynamic variations in pointing should be restricted by the design to be less than that amount. This requirement leads to a specification for nutation stability and also to a requirement to balance the spinning section.

Propellant for 7 years of spacecraft operations has been included. In the event that the solar cell array has not degraded to the point conservatively predicted and the spacecraft has not failed, the TDRS will continue to function and provide relay service as specified. This will provide a longer time to write off development and deployment costs of the system, and the expected cost-effectiveness of the system will be enhanced.

Considerable attention has been devoted during the study to cost-effectiveness. The general approach has been to utilize well proven technology for the satellite subsystems and, if compatible with launch vehicle performance limitations, to utilize hardware designed for earlier satellite programs.

4.2 CONFIGURATION SUMMARY

The baseline configuration selected for the Space Shuttle launched TDRS's in the orbital configuration is similar to the optional configuration for the Atlas-Centaur-launched TDRSs. However, the relatively large payload bay of the Space Shuttle permits a considerably easier stowage of the antenna subsystem. The electrical power subsystem has been enlarged to provide continuous voice communication service in order to take advantage of the payload capability of the Space Shuttle and maximize communication service. The transtage was selected to provide a cost-effective booster to inject an assemblage of three spacecraft simultaneously into synchronous transfer orbit. The injection capability is approximately 6600 kg. Each spacecraft has been allocated 2100 kg, allowing 300 kg for mission-peculiar equipment and installation onto the transtage.

The Space Shuttle with its 4.6 by 18.3 meter payload compartment allows stowage of the antennas around the solar cell array. A tandem arrangement of the multiple launched spacecraft is accordingly feasible. The antennas are deployed on booms and an Astromast is used to provide deployment for the VHF antenna array. Figure 28 is an artist's concept of the TDRS orbital configuration, and Figure 29 is a configuration layout drawing.

The Gyrostat stabilization concept has been employed to provide a fully stabilized platform for the payload while exploiting the simplicity and long-life advantages associated with spinning satellites. The two main elements of the spacecraft are the spinning rotor and the despun earth-oriented platform containing the communication repeater and its antennas. A rotating interface, consisting of conventional ball bearings and slip rings, sustains the relative motion between the two bodies, permits signal transfers to take place, and affords an electrical path over which power from the solar panels and batteries can flow to the repeater payload. The spinning rotor provides a basic gyroscope stability to the spacecraft.

The despun section houses the communication equipment and some of the telemetry, tracking, and command equipment. Electronic equipment is mounted on thermally controlled platforms. This configuration features despun platforms at both ends of the spacecraft to facilitate deployment of the antennas. Antennas are mounted off the platforms on mast type support structures. Short backfire type antennas are provided for the low data rate user VHF return link, the UHF forward link and the S band transponder and order wire services. Parabolic reflector antennas are provided for both forward and return link service for the medium and high data rate users. The TDRS to ground link at Ku band incorporates a high gain parabolic reflector antenna. Paraboloid reflector antennas are installed on two-axis gimbals.

The spinning section supports and houses the propulsion, electrical power, attitude control, and some of the tracking, telemetry, and command equipment. The apogee motor is installed in the central thrust tube. Hydrazine tanks are mounted on ribs extending from the thrust tube to the solar cell array. Batteries, battery controllers, despin control electronics, and telemetry tracking, and command equipment are mounted on the ribs and small equipment platforms spanning the ribs. The aft end of the spacecraft is sealed by means of a thermal barrier that protects the spacecraft equipment during apogee motor firing and minimizes heat loss during orbital operations. Attitude control sensors, the radial control jets, and umbilical connectors are installed in an annular ring between sections of the solar cell array. The axial jets are mounted on truss supports and protrude through the aft thermal barrier.

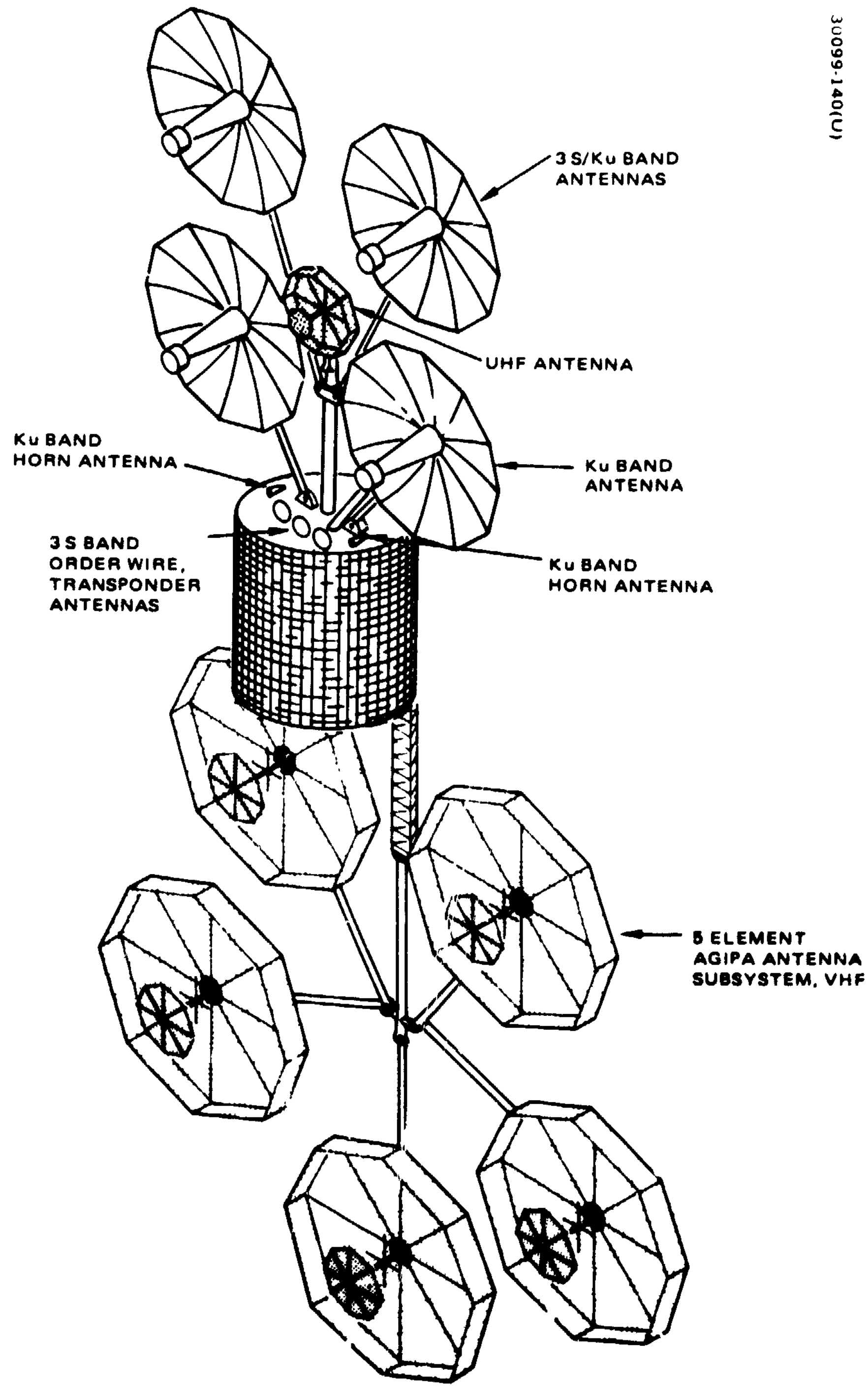


Figure 28. TDR Spacecraft

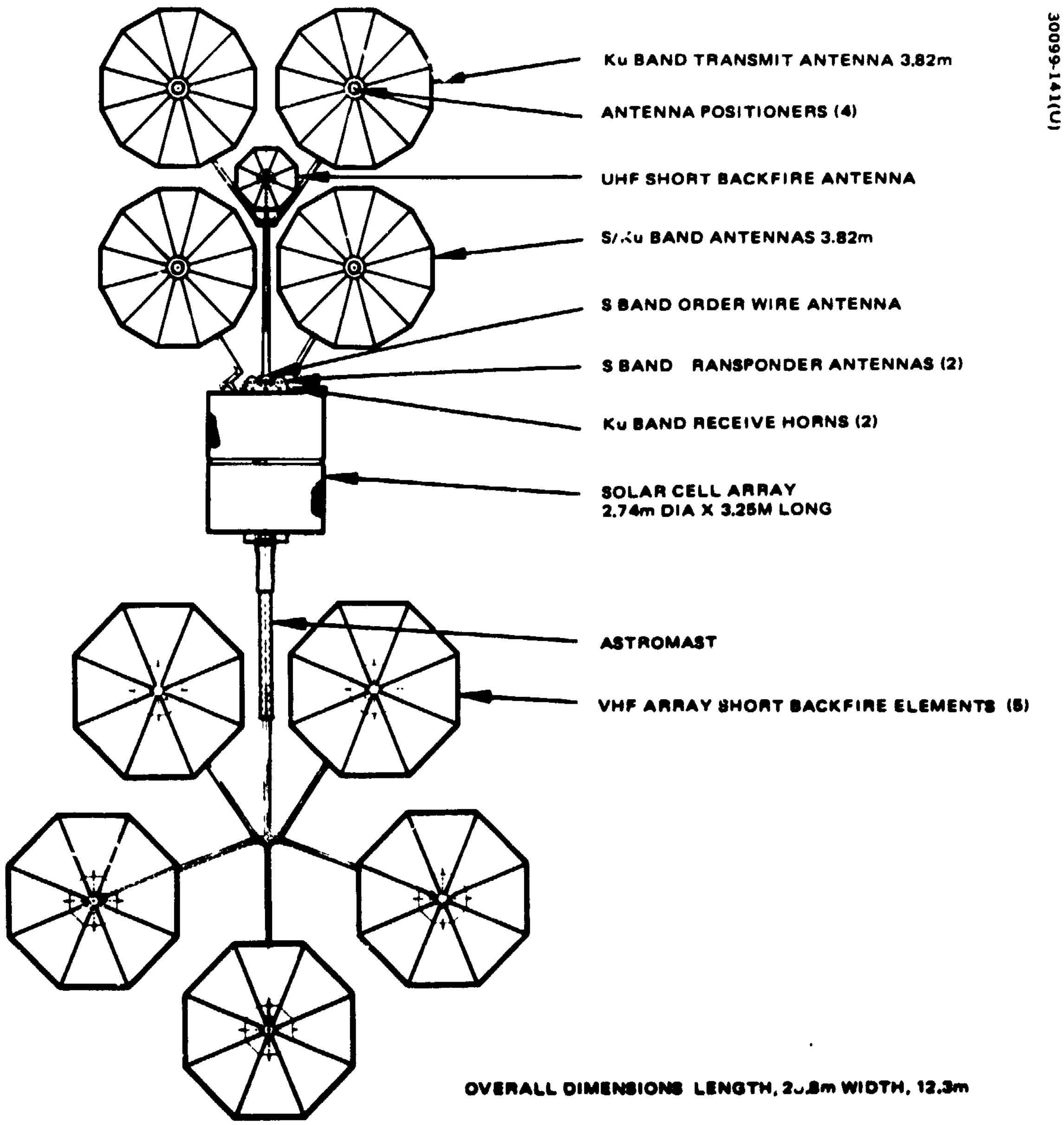


Figure 29. TDR Spacecraft Configuration

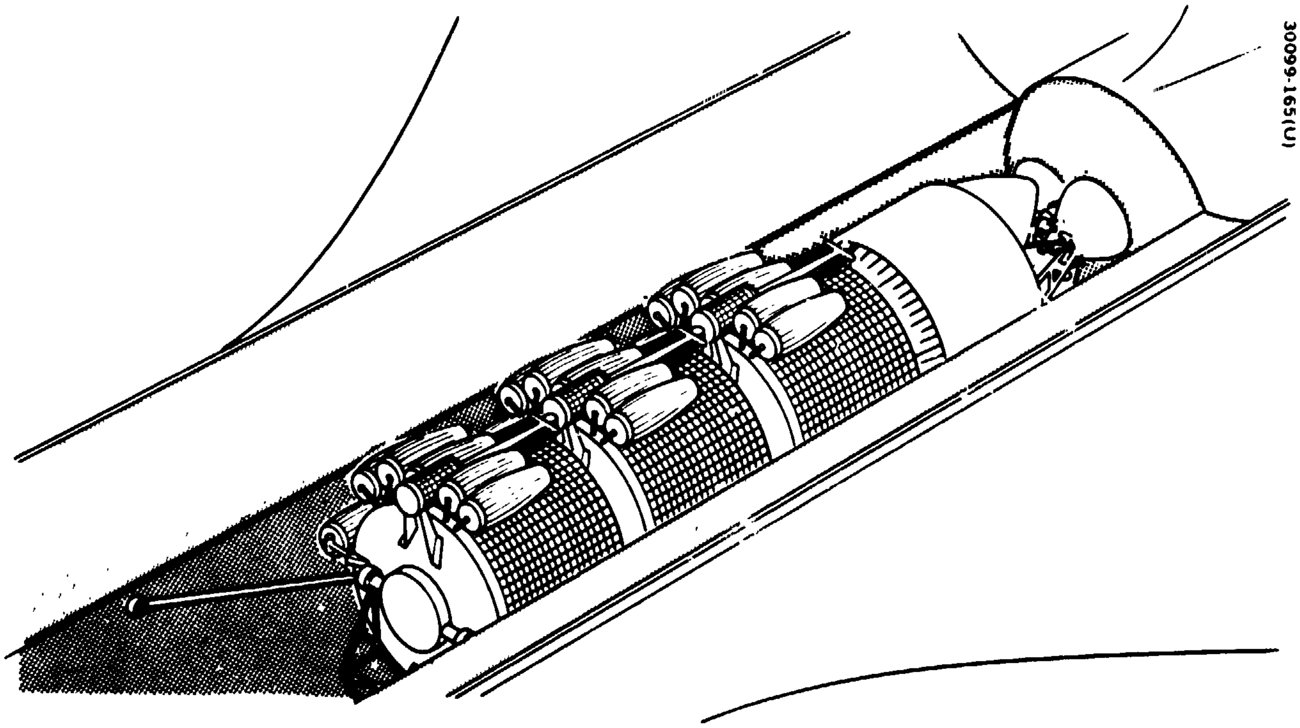


Figure 30. Spacecraft Assembly in Space Shuttle Bay

The satellites are attached to the Transtage with band release clamps. Launch loads are transmitted through a cylindrical thrust tube which supports the apogee motor and the spinning assembly of the spacecraft. The despin bearing is structurally locked out of the load path during launch and orbit injection by band release clamps. The principal load path is a cylinder approximately 1 meter in diameter which extends from one end of the spacecraft to the other. This provides a rigid column for integrating the three spacecraft into their launch configuration. A pair of launch load clamps provide a load path around the despin bearing assembly. Each spacecraft is joined to its neighboring spacecraft in the Space Shuttle with a similar clamp as shown in Figure 30. Upon separation, the spacecraft is spun up as a rigid rotor and operates in the stable spinner mode through injection into synchronous orbit. Upon ground command, the launch load clamps around the despin bearings are released, and the payload section is despun using the electrical motor drive. Antennas are subsequently deployed by a combination of ground commands and sequence release mechanisms.

Table 12 lists salient characteristics of the TDRS and the subsystem reliability is summarized in Table 13. Spacecraft power budgets are summarized in Tables 14 and 15. A spacecraft mass summary is contained in Table 16. A complete subsystem mass listing is included in Table 17.

TABLE 12. GENERAL SUMMARY

General	
Orbit	Synchronous, 3 degrees initial inclination
Launch vehicle	Space Shuttle/Transtage
Spacecraft deployment	Three per launch
Transfer orbit injection	Transtage
Synchronous orbit injection	Apogee motor
Design lifetime	5 years (RCS fuel for 7 years)
Reliability	0.717 at 5 years
Station change maneuver	2 maneuvers, 4.33 deg/day each
Configuration	
Stabilization	Gyrostat with both end platforms despun
Despun section subsystems	Antennas
	Repeaters
	Portion of TT&C
Spinning section subsystems	Electrical power
	Propulsion
	Attitude control
	Portion of TT&C
Nominal Dimensions	
Height, width (antennas deployed)	12.3, 25.8 meters
Rotor diameter	2.75 meters
In-orbit mass	1115 kg
Structure	
Thrust structure	Aluminum
Equipment mounts	Aluminum
Antenna supports	Aluminum, beryllium, and astromast
Solar cell substrate	Fiberglass/aluminum-honeycomb
Thermal Control	Thermal control cavity inside spinning solar cell array – passive design
Telecommunications Subsystem	
Low data rate command	Sequential to all LDR users
Low data rate return	Simultaneous from all LDR users, AGIPA antenna subsystem

Table 12 (continued)

LDR voice	[illegible]ntinuous service available
Medium/high data rate	Two dual-usage channels
<u>Telemetry Subsystem</u>	
PCM mode	
Word length	8 bits
Frame length	64 words main frame
	11 words subcommutated (8 subcommutations)
Analog words	110 words total
Digital words	31 words total
Bit rate	1000 bps
Code type output	Manchester
FM mode (attitude data)	
Subcarrier frequency	14.5 kHz
Data type	Real time pulses
Modulation	FM
Data transmitter	1) Sun pulses
	2) North earth pulses
	3) South earth pulses
	4) Execute receipt
<u>Command Subsystem</u>	
Tones	1, 0, and execute
Input signal	FSK/AM
Bit rate	128 bps
Command capacity maximum	255 despun, 127 spinning
Command verification via	Telemetry
Command execution	Real time
Execution synchronization	Sun or earth pulses
Maximum command rate	Approximately 4/s
<u>Antenna Subsystem</u>	
Low data rate service antennas	AGIPA consisting of five short backfire type elements
VHF	13.86 dB peak gain
UHF	Short backfire type, 14.57 dB peak gain

Table 12 (continued)

S/Ku band MDR/HDR antenna	Three, paraboloid reflector type
Peak gains	
MDR forward	35.5 dB
MDR return	36.2 dB
HDR forward	52.8 dB
HDR return	51.9 dB
Ku band ground link antenna	Paraboloid reflector
Peak gain forward	52.1 dB
Peak gain return	53.0 dB
Ground to TDRS link, Ku band	Two horns, 22.5 dB peak gain
Order wire service	Short backfire type, 14.3 peak gain
S band transponder	Two short backfire type
Attitude Control Subsystem	
Stabilization type	Gyrostat type dual spin
Nutation control	Magnetic damper and despin control dynamics
Despin control	Earth center findings with earth sensors
Power and signal transfer	Dry lubricated, silver slip rings
Despin motor	Two, independent, brushless dc, resolver commutated
Reaction Control Subsystem	
Propellant	Hydrazine
Thrusters	Six 22.24 newton thrusters
Electrical Power Subsystem	
Solar panels	(26.5 V)
23 days before equinox (EOL)	800 W
Summer solstice (EOL)	752 W
Maximum power required	768 W (batteries being charged)
Maximum bus voltage	30 V (clamped by bus limiters)
Solar Cells	
Type	2 x 6 cm, silicon n/p, 10 ohm-cm
Thickness	0.30 mm (12 mil)
Cover glass	0.30 mm (12 mil)
Eclipse power	620 W average

Table 12 (continued)

Batteries	
Number	Four
Type	Nickel-cadmium
Capacity	20 amp-hr
Maximum DOD	<48 percent
Charge rate	C/15
Trickle charge rate	C/60
Minimum bus voltage	24.5 V
Electronics	
Battery charge controller operation	Automatic or ground-commanded
Battery discharge controller operation	Automatic
Battery reconditioning	Ground-commanded (optional)
Tap limiters; operating voltage	29 to 29.5 V
Bus limiters; operating voltage	29.5 to 30 V
Apogee Injection Motor	
Type	Solid propellant, I_{sp} = 286 seconds
Velocity of injection	1756 m/s for 2100 kg initial mass

TABLE 13. OPERATIONAL SPACECRAFT RELIABILITY SUMMARY

Subsystem	5 Year Reliability Estimate
Communication and antenna positioning	0.813
Telemetry and command	0.926
Attitude control	0.956
Electric power	0.984
Harness	0.984
Reaction control	0.972
Total	0.677

TABLE 14. TDRS ELECTRICAL POWER SUMMARY
(Eclipse Season, Sunlight)

Equipment	Watts at 26.5 Volts		
	Command Mode	S Band Voice Mode	UHF Voice Mode
HDR return transmit (Ku)	66	66	66
LDR/MDR return transmit (Ku)	10	10	10
HDR forward transmit (Ku)	58	58	58
MDR forward transmit 1 (S)			
Command and data	29	29	29
Voice	-	-	-
MDR forward transmit 2 (S)			
Command and data	29	-	29
Voice	-	110	-
LDR forward transmit (UHF)			
Command and data	158	158	158
Voice	-	-	151
S band transponder	26/2	26/2	26/2
Receivers, processors, etc.	70	70	70
Telemetry, tracking, and command	16	16	16
Antenna position control	12	12	12
Despin control	20	20	20
Thermal control	6	6	6
Power electronics	18	18	18
Battery charging	94	94	47*
Distribution losses	16	16	16
Power required	629/605	710/686	732/708
Contingency	171/195	90/114	68/92
Solar power available	800	800	800

*Trickle change during UHF voice transmission.

TABLE 15. TDRS ELECTRICAL POWER SUMMARY
(Solstice Season)

Equipment	Watts at 26.5 Volts		
	Command Mode	S Band Voice Mode	UHF Voice Mode
HDR return transmit (Ku)	66	66	66
LDR/MDR return transmit (Ku)	10	10	10
HDR forward transmit (Ku)	58	58	58
MDR forward transmit 1 (S)			
Command data	29	29	29
Voice	-	-	-
MDR forward transmit 2 (S)			
Command data	29	-	29
Voice	-	110	-
LDR forward transmit (UHF)			
Command data	158	158	158
Voice	-	-	151
S band transponder	26/2	26/2	26/2
Receivers, processors, etc.	70	70	70
Telemetry, tracking, and command	16	16	16
Antenna position control	12	12	12
Despin control	20	20	[illegible]
Thermal control	6	6	
Power electronics	18	18	18
Battery charging	-	-	-
Distribution losses	16	16	16
Power required	534/510	615/591	685/661
Contingency	218/242	137/161	67/91
Solar power available	752	752	752

TABLE 16. SPACECRAFT MASS SUMMARY

Subsystem	Mass, kilograms
Repeaters	99.9
Telemetry, tracking, and command	18.5
Antennas	113.0
Attitude control	56.1
Reaction control	18.5
Electrical power	143.0
Wire harness	30.0
Apogee motor burned out	77.0
Structure	270.0
Thermal control	30.0
Contingency	184.8
Spacecraft final orbit	1040.8
Hydrazine synchronous orbit	74.2
Spacecraft, initial orbit	1115.0
Apogee motor expendables	980.0
Spacecraft, before apogee burn	2095.0
Hydrazine, transfer orbit	5.0
Spacecraft, separation	2100.0

TABLE 17. SUBSYSTEM MASS SUMMARY

Subsystem/Item	Quantity		Mass, kilograms
	Available	Required	
Repeater Subsystem			99.9
Transmitter; HDR/MDR/HDR return	2	1	16.8
Transmitter; HDR forward	4	2	12.0
Receiver; command/LDR forward	2	1	3.4
Receiver; HDR return	4	2	12.7
Receiver; MDR/HDR forward	2	1	5.1
Transmitter; MDR forward	6	3	17.4
Receiver; MDR return	6	3	4.5
Receiver; order wire	2	1	1.9
Transponder; S band	2	1	4.0
Transmitter; LDR forward	2	1	7.2
Receiver; LDR return	20	10	6.4
Frequency synthesizer	2	1	8.5
Telemetry and Command Subsystem			18.5
Despun decoder	2	1	2.7
Despun encoder and multiplexer	2	1	4.2
Spun decoder	2	1	2.7
Spun encoder and multiplexer	2	1	5.0
Despun squib driver	1	1	2.5
Spun squib and solenoid driver	1	1	0.9
Latching valve/heater driver	1	1	0.5
Antenna Subsystem			113.0
Paraboloid reflector (Ku band) (1)	2	2	7.9
Horns (Ku band)	2	2	0.5
Paraboloid reflector (S/Ku band) (3)	2	2	26.7
Backfire (S band)	3	3	1.5
Backfire, UHF	1	1	2.5
Backfire, VHF	5	5	30.5
Turnstile, VHF	1	1	1.0
Antenna positioner	4	4	16.8
Positioner controller	4	4	3.6
Coaxial waveguide	4	4	22.0
Attitude Control Subsystem			56.1
BAPTA	1	1	32.0
Earth sensors	3	2	2.8
Sun sensor	1	1	0.1
Despun control electronics	2	1	4.4
Active nutation control	2	1	1.8
Nutation damper	2	1	15.0

Table 17 (continued)

Subsystem/Item	Quantity Available	Quantity Required	Mass, kilograms
Reaction Control Subsystem			18.5
Tanks	4	4	9.5
Thrusters	6	3	3.0
Filters	4	4	0.6
Valves fill vent	1	1	0.3
Valves latching	5	5	0.5
Pressure transducer	2	2	0.5
Plenum chambers	2	2	0.2
Manifold fittings			2.3
PO pressurant			1.6
Electrical Power Subsystem			143.0
Solar panels	2	2	46.0
Batteries	2	2	73.0
Battery controller	2	2	17.0
Heater controllers	1	1	1.1
Miscellaneous hardware			0.5
Voltage limiter	10	6	5.4
Wire Harness			30.0
Apogee Motor Burned Out	1	1	77.0
Structure			270.0
Solar array substrate	2	2	45.0
Spin structure	1	1	60.0
Despun equipment platform	1	1	60.0
Equipment support	1	1	20.0
Antenna support	-	-	65.0
Despun clamp	1	1	15.0
Balance mass			5.0
Thermal Control			30.0
Spin thermal equipment	1	1	20.0
Despun thermal equipment	1	1	10.0

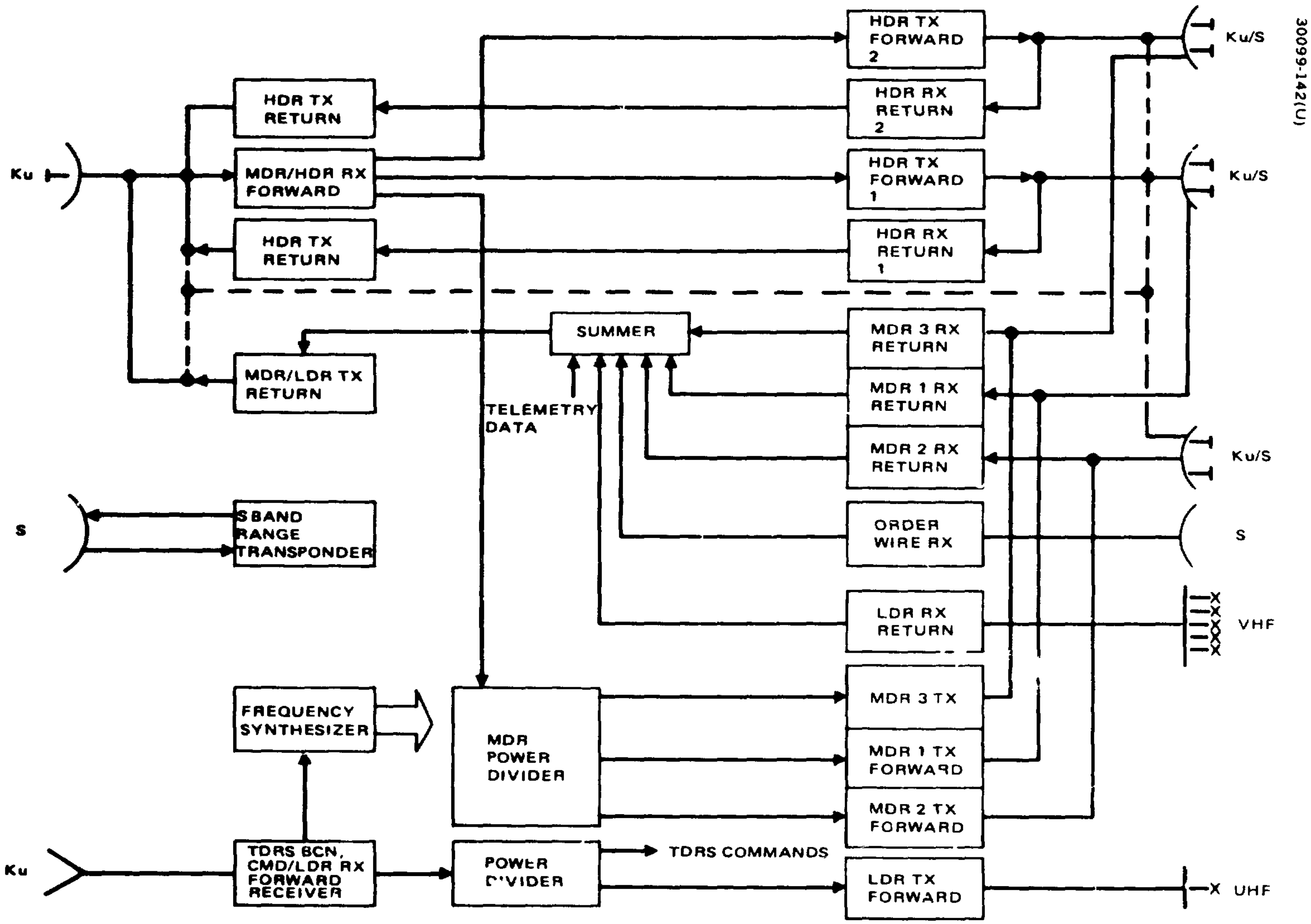


Figure 31. TDRS Repeater

4.3 SUBSYSTEM DESCRIPTION

The Space Shuttle launched TDRSs is comprised of nine major subsystems whose functional and performance characteristics are described in the following sections.

4.3.1 Telecommunication Service System

The TDRS telecommunication service system is designed to provide low data rate, medium data rate, and high data rate services. The low data rate return link includes a VHF AGIPA concept for RFI rejection and includes voice data transmissions for manned spacecraft users. The MDR service is provided at S band with a 2 kbps command data rate capability plus voice data to manned users. Two simultaneous plus one redundant two-way channels are provided with a return link data rate capability of 1 Mbps. Other S band services include an order wire receiver and an S band transponder. The transponder provides the capability of direct ranging by trilateration from ground stations other than the TDRSS ground terminal. Backup and initial TT&C operations are also carried out through the S band transponder equipment. Two HDR channels are provided at Ku band frequencies where adequate bandwidths are available for the necessary 50 Mbps forward and 100 Mbps return link data rates. Available technology allows the performance requirements to be met with state-of-the-art hardware devices. The space-to-space MDR and HDR links use three interchangeable dual-feed S/Ku band antennas. The TDRS telecommunication service subsystem requirements are summarized in Table 18.

The simplified block diagram of Figure 31 illustrates the TDRS repeater subsystem design configuration providing the required telecommunication service. The repeater is a frequency translation type that provides coherent frequency translations at all bands. It includes an S band order wire capability and an S band ranging transponder. Every active element in the repeater subsystem is redundant.

A multichannel Ku band receiver receives ground-transmitted command, voice and beacon signals through an earth-coverage horn antenna. TDRS commands are sent to the TT&C subsystem, the beacon signal is processed and phase locked to a frequency synthesizer reference source to provide coherency, and the LDR command and voice data are distributed via a power divider to the UHF transmitter for frequency upconversion and radiation to user spacecraft. A multichannel Ku band receiver and high gain antenna are used for the three MDR channels and two HDR channels. The MDR signals may be transmitted to the user spacecraft over three S band links. Upon return, the S band MDR data from user spacecraft are double-conversion frequency-translated to a Ku band link for transmission to the ground. A linear Ku band transmitter is used for MDR, LDR and telemetry information. The HDR channels are transmitted to the users at Ku band and received at Ku band.

TABLE 18. TDRS TELECOMMUNICATION SERVICE SUBSYSTEM REQUIREMENTS

LDR Forward Link (to user)	
Forward link EIRP	30 dBW/channel
Number of channels	Two
Frequency	400.5 to 401.5 MHz
Field of view	30 degrees
Coding	PN
Antenna	Backfire, single UHF
Data rate	300 bps command 9.6 kbps voice
RF bandwidth	1 MHz
LDR Return Link (from user)	
Return link G/T per element	-13.5 dB/K
Number of channels	Twenty
Frequency	136 to 138 MHz
Voice modulation	Delta modulation
Telemetry coding	Code division multiplexing Convolution encoding
Antenna	5 element AGIPA
Data rate	19.2 kbps voice, 1.2 kbps telemetry
RF bandwidth	2 MHz
MDR Forward Link (to user)	
Forward link EIRP	47 dBW 41 dBW
Number of channels	Three
Frequency	2038 to 2118 MHz
Field of view	2.8 degrees
Antenna	Dual-feed paraboloid
Data rate	2 kbps command 24 kbps voice (2 signals)
RF bandwidth	30 MHz channel
MDR Return Link (from user)	
Return link G/T	10.2 dB/K
Number of channels	Three
Frequency	2218 to 2298 MHz
Antenna	Dual-feed paraboloid
Data rate	1 Mbps telemetry (maximum)
Order wire G/T	-15.2 dB/K
RF bandwidth	10 MHz
HDR Forward Link (to user)	
Forward link EIRP	59 dBW 51 dBW
Number of channels	Two
Frequency	Channel 1: 14.76 to 14.81 GHz Channel 2: 14.86 to 14.91 GHz

Table 18 (continued)

Antenna	Dual-feed paraboloid
Data rate	50 Mbps
RF bandwidth	50 MHz
HDR Return Link (fron user)	
Return link G/T	93.2 dB/K
Number of channels	Two
Center frequencies	13.800 13.950
RF bandwidth	100/50/10 MHz
Antenna	Dual-feed paraboloid
Data rate	100 Mbps
MDR/LDR Return Link (to ground)	
Return link EIRP	53.1 dBW
Number of channels	Three MDR (10 MHz each) Ten LDR (2 MHz each) One TDRS telemetry One order wire
Frequency	14.60 to 14.71 GHz
Antenna	Paraboloid
Data rate	1 Mbps maximum
RF bandwidth	110 MHz
HDR Return (to ground)	
Return link EIRP	59 dBW 51 dBW
Number of channels	Two
Frequency	Channel 1: 14.96 to 15.06 GHz Channel 2: 15.1 to 15.2 GHz
Antenna	Paraboloid
Data rate	100 Mbps
MDR/HDR Forward Link (from ground)	
Forward link G/T	17.3 dB/K
Number of channels	Two HDR (50 MHz) Three MDR (30 MHz)
Frequency	13.460 to 13.7 GHz
Antenna	Paraboloid - HDR MDR
Data rate	HDR 50 Mbps MDR 1 Mbps maximum
RF bandwidth	240 MHz

Table 18 (continued)

S Band Ranging Transponder	
Transmit EIRP	20 dBW
Number of channels	One
Frequency	
Transmit	2210 MHz
Receive	2029 MHz
Antennas transmit and receive	Short backfire type
RF bandwidth	8 MHz
TDRS CMD, Beacon and LDR Forward Link (from ground)	
Forward link G/T	-13.2 dB/K
Number of channels	One LDR
	One beacon
	One command
Frequency	13.4 to 13.42 GHz
Antenna	Horn
RF bandwidth	20 MHz

TABLE 19. TDRS REPEATER RECEIVER CHARACTERISTICS

Receiver	Frequency Band	Bandwidth, MHz	Noise Temperature, K	Preamplifier Type
MDR/HDR forward	Ku	230	2600	None
HDR return	Ku	200/100/50/10	440	Paramp/ TDA
TDRS BCN, CMD, LDR forward	Ku	20	1170	TDA
MDR return	S	10	100	Paramp
Order wire	S	1	420	Transistor
LDR return	VHF	2	420	Transistor
S band transponder	S	8	420	None

The VHF antenna is a five-element array utilizing the AGIPA concept. Therefore, the LDR return link contains 10 channels of VHF polarization and phase data to be processed on the ground in an attempt to overcome RFI degradations. The HDR and MDR user links utilize dual-feed parabolic reflectors, one for each MDR channel, and an RF switch to select the antenna to be used for the HDR channel.

The communication repeater receiver characteristics listed in Table 19 are those of typical current state-of-the-art hardware. The Ku band receivers having noise temperatures of 440, 1170, and 2600 K are achieved using parametric amplifiers, tunnel diode amplifiers, and low noise mixers in various combinations. Transistor low noise preamplifiers are used at VHF frequencies to achieve a 420 K noise temperature, and parametric amplifiers are employed for the S band MDR return link receivers.

TABLE 20. TDRS TRANSMITTER CHARACTERISTICS

Transmitter	Frequency Band	EIRP High/Low, dBW	Antenna Gain dB	RF Loss, dB	PA Output High/Low, Watts	Amplifier Efficiency High/Low, Percent	PA dc Power High/Low, Watts	Total dc Power* High/Low, Watts
HDR return	Ku	59/51	52.8	2.7	7.8/1.2	33/20	23.6/6.0	29.6/8.6
HDR forward	Ku	59/51	52.8	2.2	6.9/1.1	33/20	20.9/5.5	26.2/7.8
LDR/MDR return	Ku	53.1	52.8	2.7	2.0	30	6.7	8.4
LDR forward	UHF	33/30	12.5	1.0	142/71	51/51	280/140	286/146
MDR forward	S	47/41	35.5	2.8/3.0	27/6.3	28/30	96/21	102/27
Range transponder	S	20	13.5	1.4	6.3	30	22	24

*Includes upconverter, driver, and regulator.

The transmitter characteristics are listed in Table 20. The required EIRP for each transmitter is shown and the major gain and loss contributors leading to the required dc power are listed also to illustrate the derivation of the total power required of each transmitter.

The repeater has several bands of operating frequencies and requires a variety of transmitters. The transmitters are the repeaters' largest power consumer; therefore, design emphasis is placed on transmitter efficiency. All but the Ku band TWTs are solid state devices. The TWTs have a dual-mode power capability that is accomplished by command control of the tube anode and helix voltages. The transistor power amplifiers used in the S band and UHF transmitters are operated at maximum efficiency and are paralleled to satisfy the total power output requirement. The TWT amplifiers are redundant and the transistor amplifiers are selectable as three of four or four of six to provide excellent reliability.

The repeater subsystem component mass summary is given in Table 21. Available quantities represent the redundancy and spare components. The required quantity represents the portions used or turned on to provide the telecommunication service.

4.3.1.1 Telecommunication Repeater Design Description

The TDRS communication repeater subsystem is designed to provide LDR, MDR, and HDR links between the user spacecraft and a central ground station. The LDR link is accomplished at VHF frequencies using the senior AGIPA antenna system for RFI rejection. Three independent MDR links are provided at S band. Each link will allow two voice signals plus 2 kbps data to be transmitted to a user spacecraft and up to 1 Mbps telemetry data to be returned. However, only two links are considered operational; the third link

TABLE 21. MASS AND POWER REQUIREMENTS FOR REPEATER COMPONENTS

	Spacecraft Quantity	Mass, kilograms	Dc Power, watts
Transmitter; HDR/MDR/LDR Return		16.8	70.0
Antenna switches	2	0.4	-
Multiplexer (3 transmit and 1 receive)	1	0.5	-
TWT and EPC	6	8.2/2.3	67.6
Driver upconverter	6	3.3	2.4
Summer	1	0.3	-
Transmitter; HDR Forward		12.0	54.0
Antenna switches	6	1.2	
Diplexer (transmit/receive)	2	0.4	-
TWT and EPC	4	5.2	52.4
Driver upconverter	4	2.2	1.6
Receiver; Command/LDR Forward		3.4	2.1
TDA and BPF	2	0.7	0.4
Mixer/amplifier and phase lock loop	2	2.5	1.7
Hybrid and divider	1	0.1	-
EPC	1	0.1	-
Receiver; HDR Return		12.7	20.0
Tracking modulator	3	3.3	3.4
Preamplifier	4	5.0	10.8
Mixer/amplifier/filter (redundant)	4	2.4	1.2
Tracking demodulator	4	0.2	3.6
EPC	1	0.2	1.0
Receiver; MDR/HDR Forward		5.1	5.8
Tracking modulator	1	1.1	1.7
Bandpass filter	1	0.1	-
Mixer/amplifier/filters	2	2.9	2.0
Antenna tracking demodulator	1	0.9	1.7
EPC	1	0.1	0.3
Transmitter; MDR Forward		17.4	102/27
Driver (redundant)	6	8.1	6.0
Power amplifier (4 of 6)	3	3.9	96/21
Diplexer and cable	3	5.1	-
EPC	3	0.3	-
Receiver; MDR Return		4.5	17.5
Preamplifier	6	2.4	15.0
Mixer/filter/amplifier/attenuator (redundant)	6	1.8	1.5
EPC	3	0.3	1.0

Table 21 (continued)

	Spacecraft Quantity	Mass, kilograms	Dc Power, watts
Receiver; Order Wire		1.9	1.7
Bandpass filter	1	1.1	-
Preamplifier	2	0.2	0.5
Mixer/filter amplifier/mixer amplifier	2	0.5	1.0
EPC	1	0.1	0.2
Transponder; S Band		4.0	24.0/2.0
Receiver	2	0.6	1.0
Transmitter	2	0.9	22.0
Frequency reference	2	0.3	1.0
Filters	1	2.2	-
Transmitter; LDR Forward		7.2	286.0/146.0
Driver	2	0.6	6.0
Power amplifier (4 or 8 of 10)	10	2.5	140.0/280.0
Summer and switch	1	1.0	-
Low pass filter	1	1.0	-
Cable	1	1.0	-
EPC	-	2.0	-
Receiver; LDR Return		6.4	9.6
Preamplifier/BPF/amplifier	20	1.7	1.0
Local oscillator frequency source and selector	2	0.2	0.3
Preamplifier/mixer/amplifier	20	1.1	7.0
Bandpass filter/limiter/summer	1	0.7	-
Mixer/amplifier/filter	2	0.1	0.8
EPC	1	0.1	0.5
Cable and integrated package	-	2.5	-
Frequency Synthesizer		8.5	7.8
Master oscillator and multiplier	2	8.4	7.3
EPC	1	0.1	0.5
		8.5	7.8

provides redundancy only. Other S band services include an order wire receiver and an S band ranging transponder. The transponder is compatible with present GRARR ground terminals and will provide direct ranging measurements for trilateration with three ground stations. HDR services are provided at Ku band with a 50 Mbps capability forward (to the user) and a 100 Mbps capability on the return link (from the user).

Repeater features include:

- Coherent frequency translation type
- All active elements are redundant
- Dual mode TWT power amplifiers at Ku band
- Selectable Ku band transmitter/receiver and antenna combinations
- Solid state S band and VHF power amplifiers
- Design includes IC and MIC components throughout
- VHF senior AGIPA antenna concept in the LDR return link
- Ku band tracking antennas
- Low noise receivers with minimum complexity
- High efficiency transmitters

The following repeater design description is divided into groups of units according to their operating frequency. The repeater frequency plan in Figure 32 summarizes the operational bands.

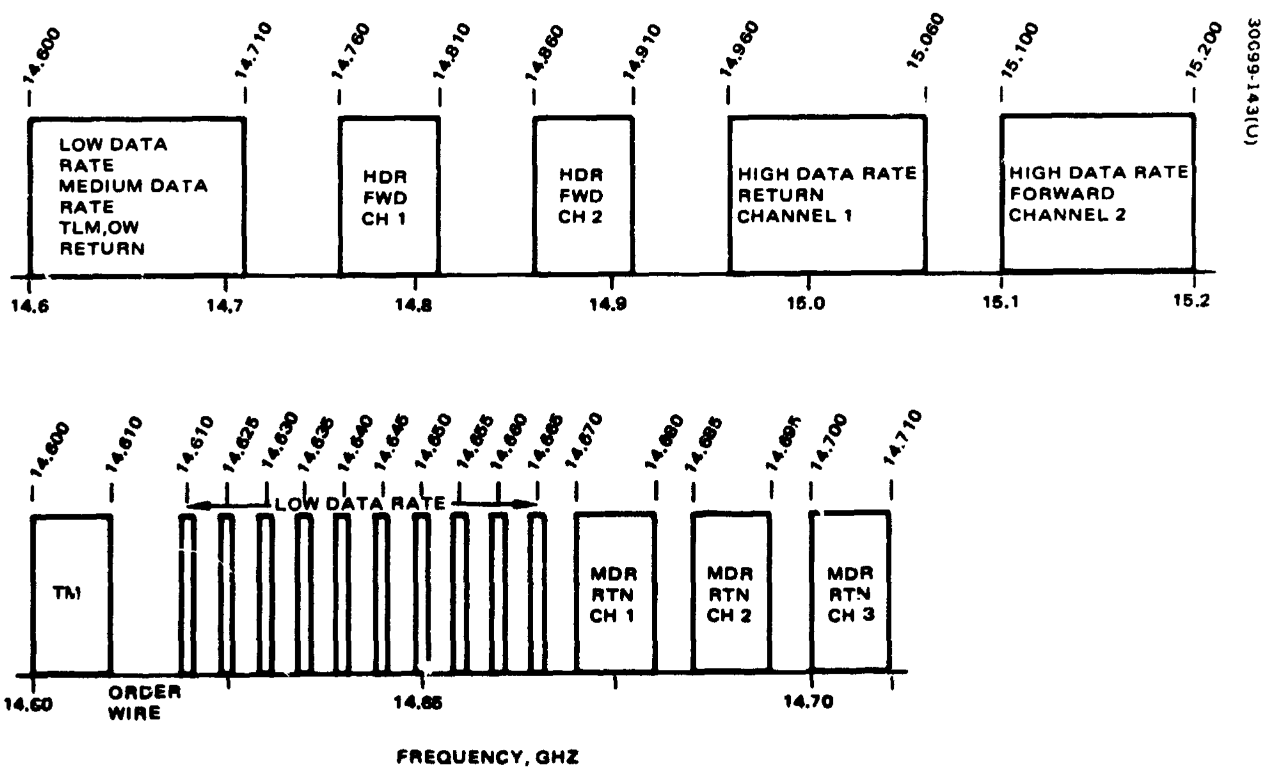
4.3.1.2 <u>Ku Band Repeater Units</u>

The TDRS repeater subsystem units operating at Ku band consist of three transmitters and four receivers. The HDR forward link transmitter and return link receiver are duplicates, thus providing dual HDR services. Each of the receivers is designed to provide antenna tracking error signals derived from the antenna tracking modulators. The Ku band antennas used for the TDRS- r link are dual-feed S/Ku band parabolic reflectors interchangeable between Ku band transmitters and receivers.

The Ku band antenna tracking modulator is shown in Figure 33. The narrow beam Ku band antennas require precision tracking to maintain the HDR link performance requirements. This is provided by a ferrite switch modulator in the monopulse difference channel outputs from the antenna. The sum channel is diplexed with the transmitter and receiver and the receiver input is therefore a composite signal containing data and tracking modulation. The tracking error signals are processed by a tracking demodulator in each Ku band receiver and applied to the antenna tracking control circuits. Dual switch drivers provide redundancy for the only active circuits in the modulator/diplexer.

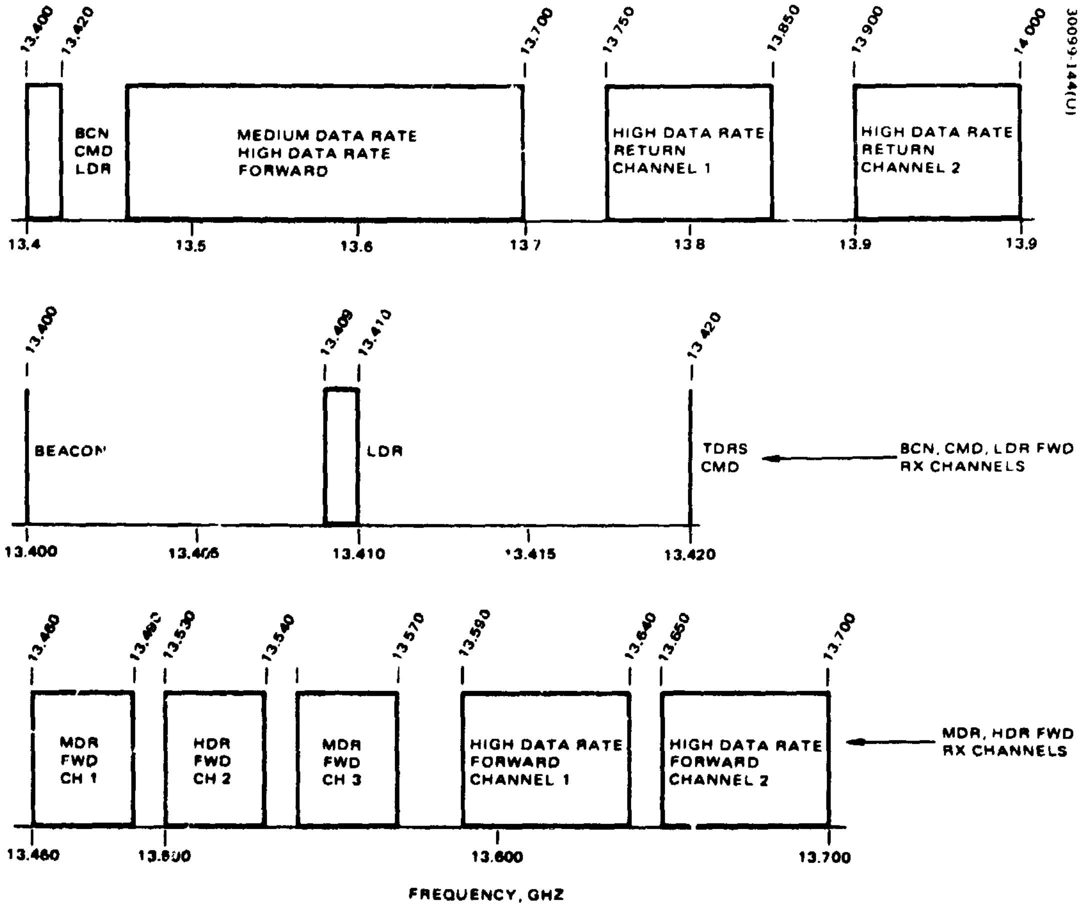
The antenna switching network is shown in Figure 34. The Ku band antennas may be used interchangeably with the Ku band transmitters and receivers. Three antennas have dual feeds for the three S band transmitters and receivers. A Ku band forward link and return link may be completed using any two of the four Ku band antennas. The switches are of the ferrite latching switch type and this configuration or matrix represents the maximum switching capability within reasonable RF loss considerations. The switches will provide added assurance of a completed HDR link in the event of antenna deployment failure. Antennas A, B, C or D may be connected to the ground link transmitter and receiver B, C, or D to the HDR TDRS/user 1 transmitter and receiver. Antennas C or D may be connected to the HDR TDRS/ user 2 transmitter and receiver. The S band MDR transmitters and receivers are assigned specific antennas, B, C, and D.

There are two HDR forward link transmitters to provide two independent 50 Mbps channels to two user spacecraft simultaneously The upconverter and traveling wave tube power amplifier are shown in the block diagram of Figure 35 for a single transmitter.

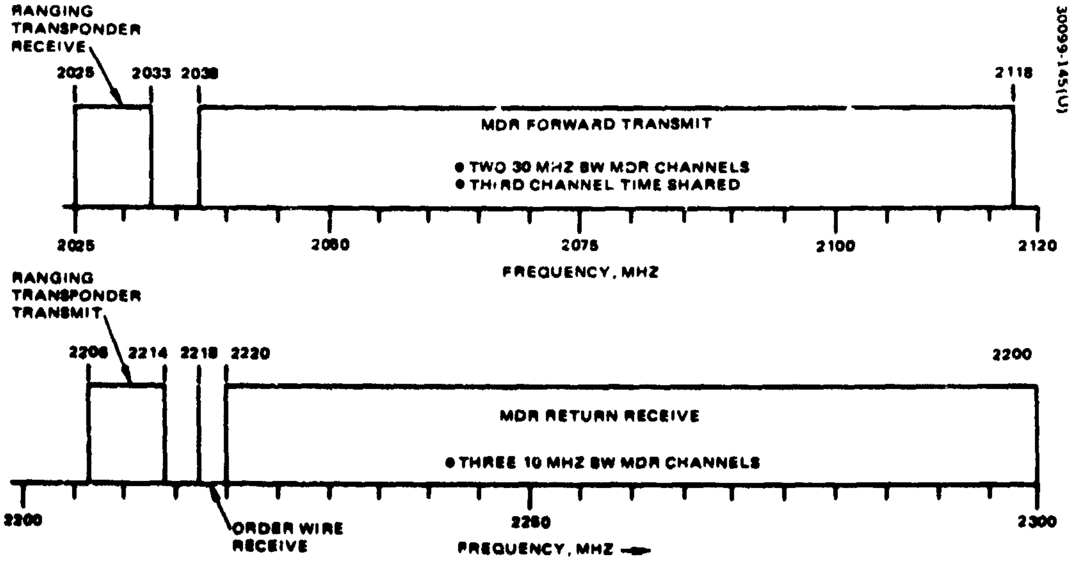


a) Ku BAND TRANSMIT

Figure 32. Frequency Plan



b) Ku BAND RECEIVE



c) S BAND TRANSMIT AND RECEIVE

Figure 32 (continued). Frequency Plan

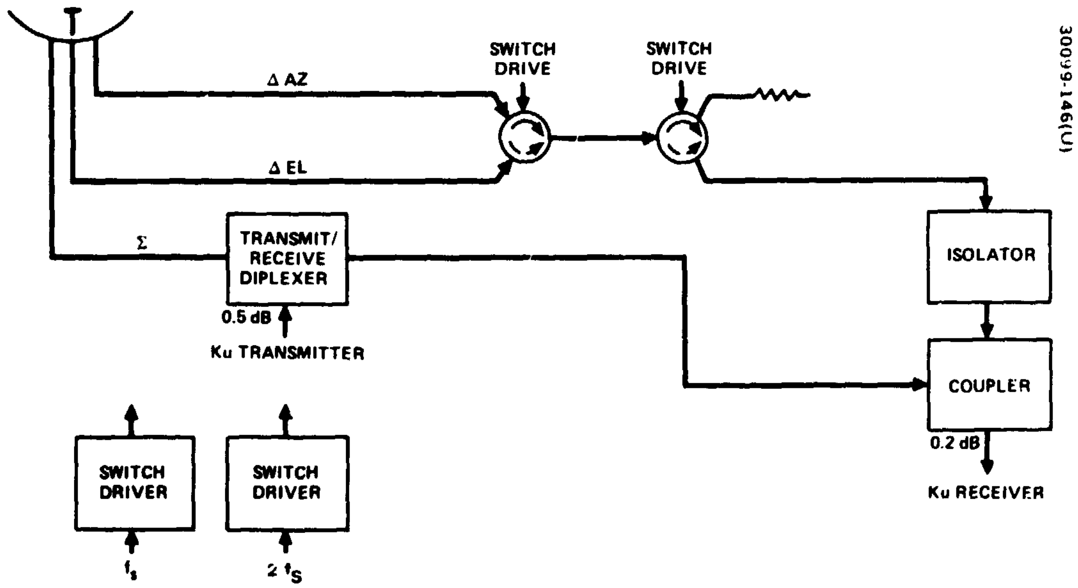
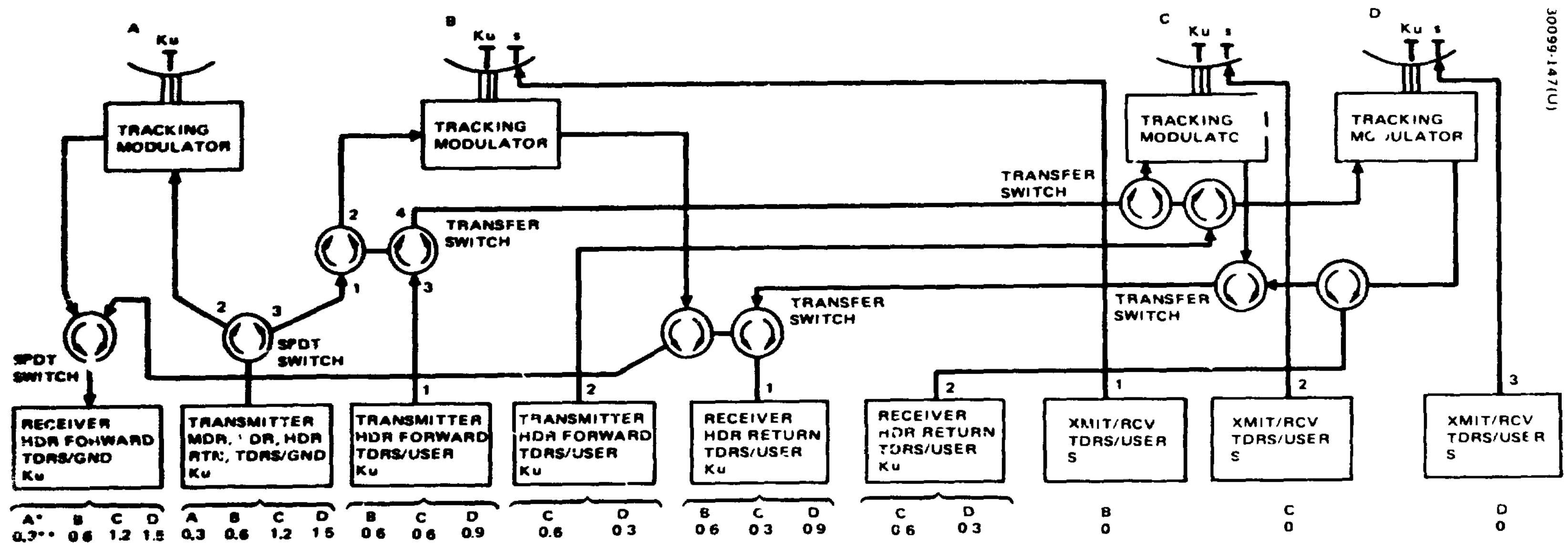


Figure 33. Ku Band Antenna Tracking Modulator/Diplexer



* SWITCH ICT FOR ANTENNA A
** TRANSMISSION OR RECEPTION LOSS DUE TO SWITCHING dB

Figure 34. Antenna Switching Network

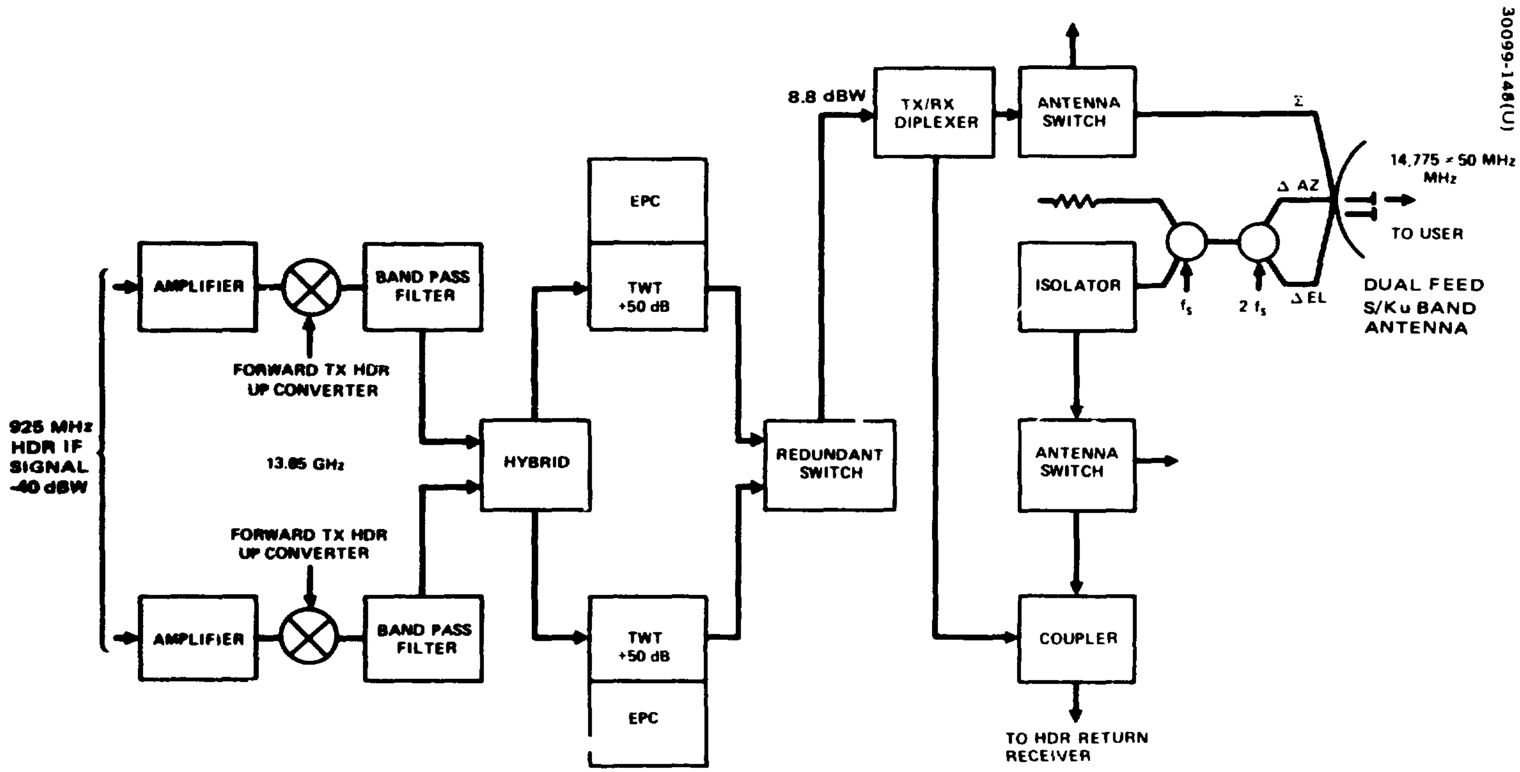


Figure 35. HDR Forward Link Transmitter and Upconverter

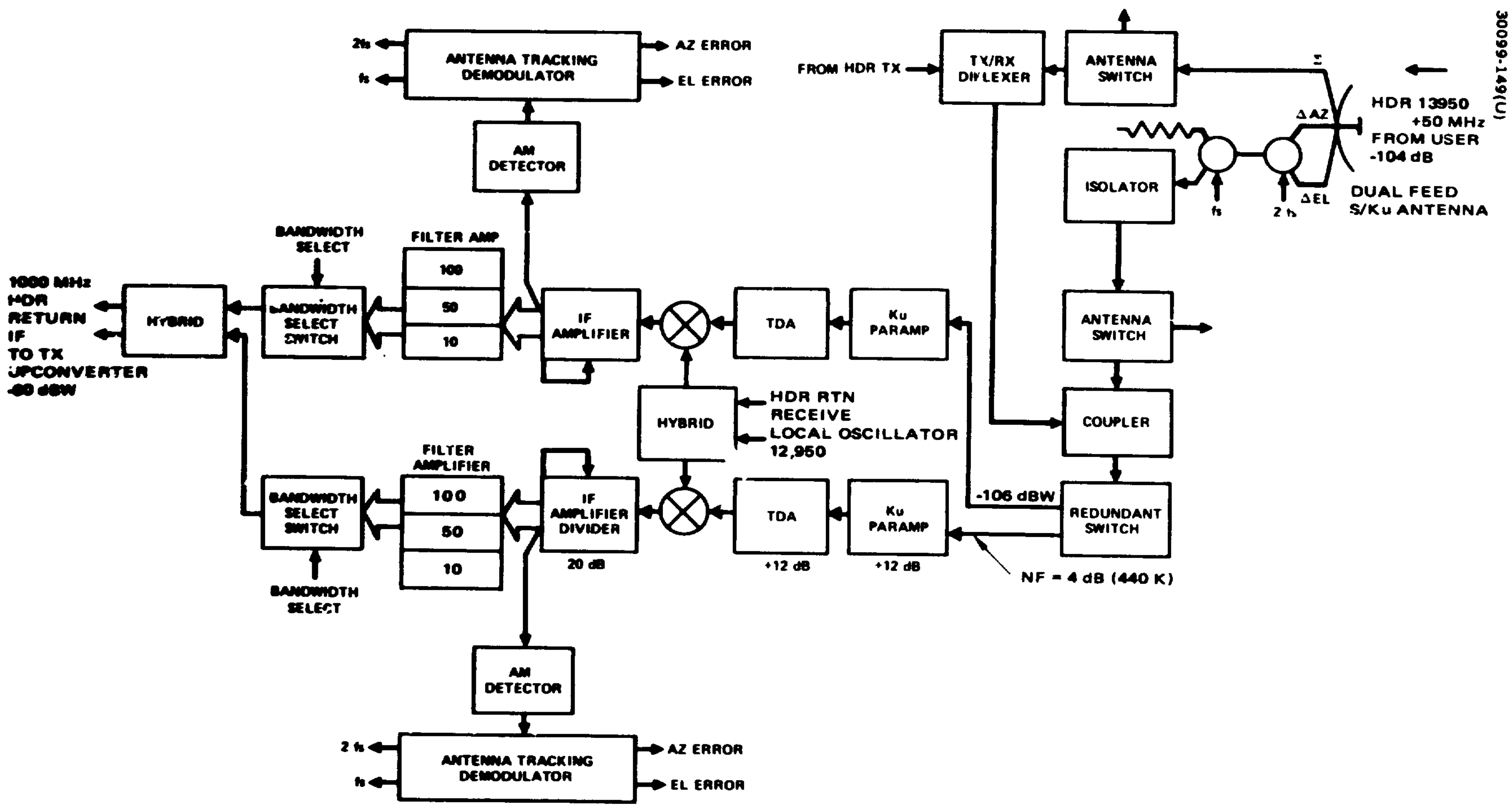


Figure 36. HDR Return Link Receiver

The HDR channel signals leave the TDRS on a 14.775 or 14.875 GHz carrier. A 50 dB gain TWT operated near saturation provides the required 8.8 dBW output power. A low power 0.8 dBW mode is possible by command control of the TWT anode and helix voltages. The TWT amplifier selected is a version of space TWT designs under present development. The key performance parameter is efficiency, which is about 33 percent in the high power mode and 20 percent in the low power mode. This efficiency is achieved by operating the TWT at a voltage 8 percent over that corresponding to maximum gain. A cathode wearout life of 10 years is well within the state of the art.

The two HDR return link receivers provide two independent 100 Mbps channels from two user spacecraft simultaneously. The input signal level of -104 dBW is received on either 13.800 or 13.950 GHz carriers. Figure 36 is a block diagram of a return link HDR receiver.

The HDR return link receiver requires a 440 K noise temperature preamplifier. To meet this requirement, a two-stage preamplifier will be employed consisting of a parametric amplifier first stage followed by a tunnel diode amplifier providing an overall gain of 24 dB. Pump power for the parametric amplifier will be provided by a Gunn diode oscillator and, with the thermal stabilization, reliable stable gain operation of the preamplifier can be assured. A receiver bandwidth of 100, 50, or 10 MHz may be selected by ground command, thus enabling optimization of the link for any user bandwidth requirements.

The data transmitted to the TDR spacecraft from the ground are received by two Ku band receivers. One receiver handles the HDR and MDR information channels and the other handles the LDR channel, as well as TDRS telemetry command signals and the reference frequency beacon signal.

The uplink MDR and HDR signals are received by a narrow beam Ku band parabolic antenna. Difference channel outputs are combined with the sum channel output after switching and phase shifting accomplished in the tracking modulator. The input to the receiver contains the 13.46 to 13.7 GHz carrier with uplink data modulation and the pseudo-monopulse amplitude modulation tracking error signals. Figure 37 is a block diagram of the MDR/HDR forward receiver.

The receiver processes the composite data and tracking signals through redundant mixer and amplifier filter circuits. The tracking modulation is processed in the antenna tracking demodulator to provide quadrature coordinate error signals. The demodulator is also the source of the two modulator switch driver signals. The receiver has no preamplifier and the noise temperature at the input bandpass filter is 2600 K. The moderate IF allows the use of transistor amplifiers for processing the tracking signal and increasing the drive level to the upconverter. The MDR and HDR signals are frequency-multiplexed and there are separate receiver outputs for each service. The MDR IF signals are distributed to the MDR forward S band transmitters and the HDR IF signals are connected to the HDR forward Ku band transmitters.

The uplink TDRS commands, LDR, and beacon signals are received on a low gain earth-coverage horn antenna having 18.5 dB gain. The carriers are within the 13.400 to 13.420 GHz band and arrive with a signal level of approximately -115 dBW. Figure 38 is a diagram of the receiver.

A tunnel-diode preamplifier is used to establish a low noise temperature at the receiver input of 1,170 K. After a first conversion to IF, the signals are separated and converted to a second IF. The beacon signal is used to phase lock a VCXO to the uplink carrier and establish a stable coherent reference signal as a source for all TDRS local oscillator and upconverter signals. The command/LDR forward link receiver is redundant and uses dual series dissipative regulators. Hybrid circuit designs are used to minimize mass. The receiver data outputs (MDR, LDR, and TDRS commands) are distributed to their respective transmitters or processors via a six-way power divider.

The K band downlink MDR, LDR and telemetry signals are transmitted on 14.6 to 14.71 GHz carriers and the HDR channels use the 14.96 to 15.2 GHz band. Figure 39 is a block diagram of the downlink transmitters.

The HDR return link transmitters are similar to the HDR forward link transmitter. The HDR transmitters are combined with the MDR/LDR transmitter via a transmit multiplexer to radiate from a common Ku band antenna. The MDR/LDR transmitter is operated in a linear region, at 5 dB backoff, since there are several data channels simultaneously processed. The TWT saturated output power is 3.6 dBW for the MDR/LDR transmitter. The TWT outputs for the HDR transmitter are 9.4 dBW for the high power mode and 1.3 dBW for the low power mode.

4.3.1.3 <u>S Band Repeater Units</u>

The telecommunication repeater S band subsystem units provide the required MDR transmit and receive, order wire receive, and trilateral ranging functions.

There are three MDR transmitters and receivers required to provide service to three separate user spacecraft. A single transmitter receiver design is illustrated by the block diagram of Figure 40.

The MDR IF signal is frequency-translated to S band antennas for solid-state amplifier to one of the three dual-feed S/Ku band antennas for transmission to a user spacecraft. The transmit frequency is selectable in the 2025 to 2120 MHz band by a commandable upconversion local oscillator frequency of 1968 to 2096 MHz. The driver output is switched directly to the antenna in the case of low power mode operation or is switched to pass through a bank of transistor amplifiers that are summed to provide a high power output. The receiver employs a parametric amplifier for the first stage, providing a noise temperature at the receiver input of 150 K. The receiver is also frequency-selectable by command within the 2200 to 2300 MHz band. A step attenuator at the IF output controls the MDR return signal level driving the MDR return transmitter.

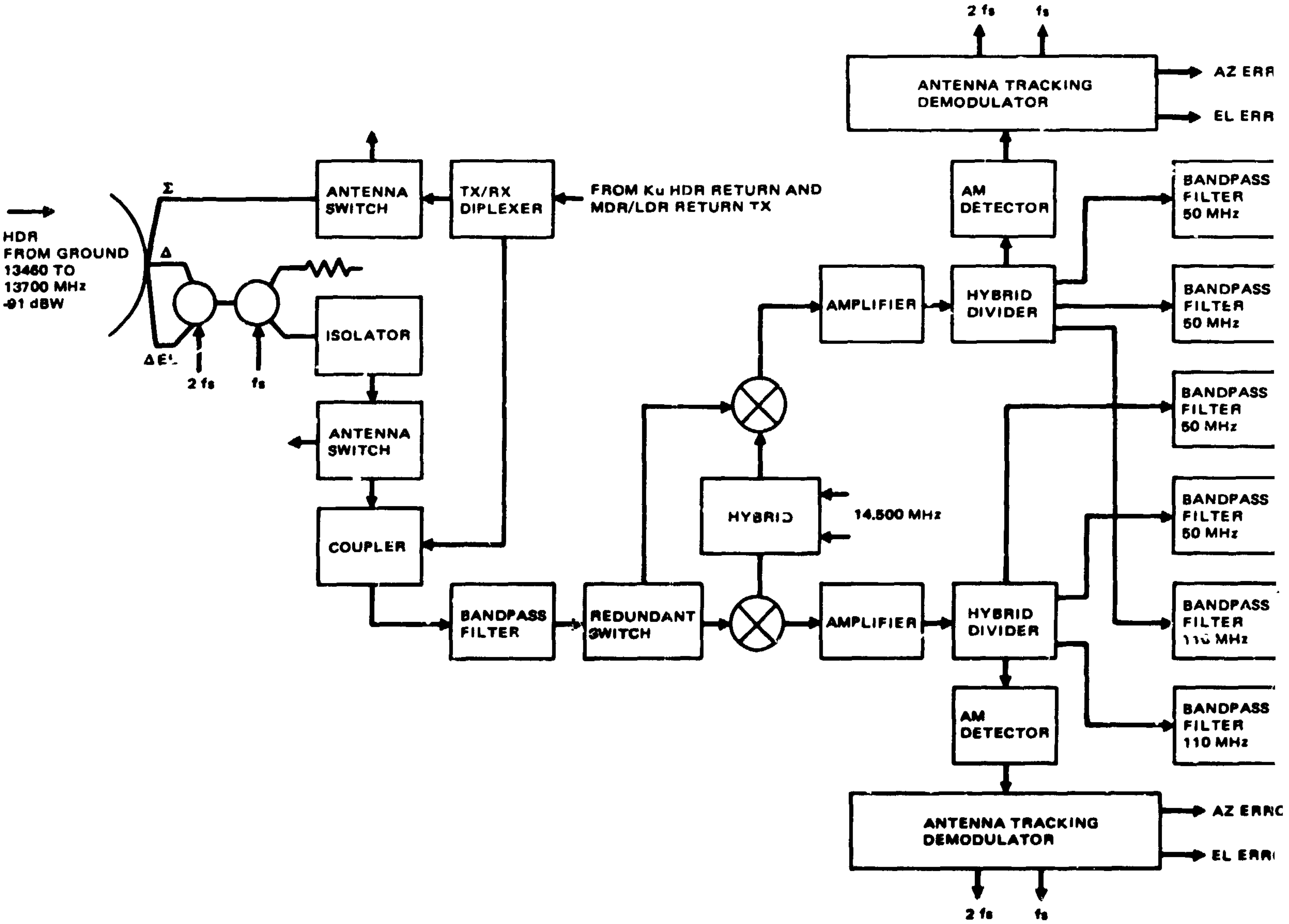
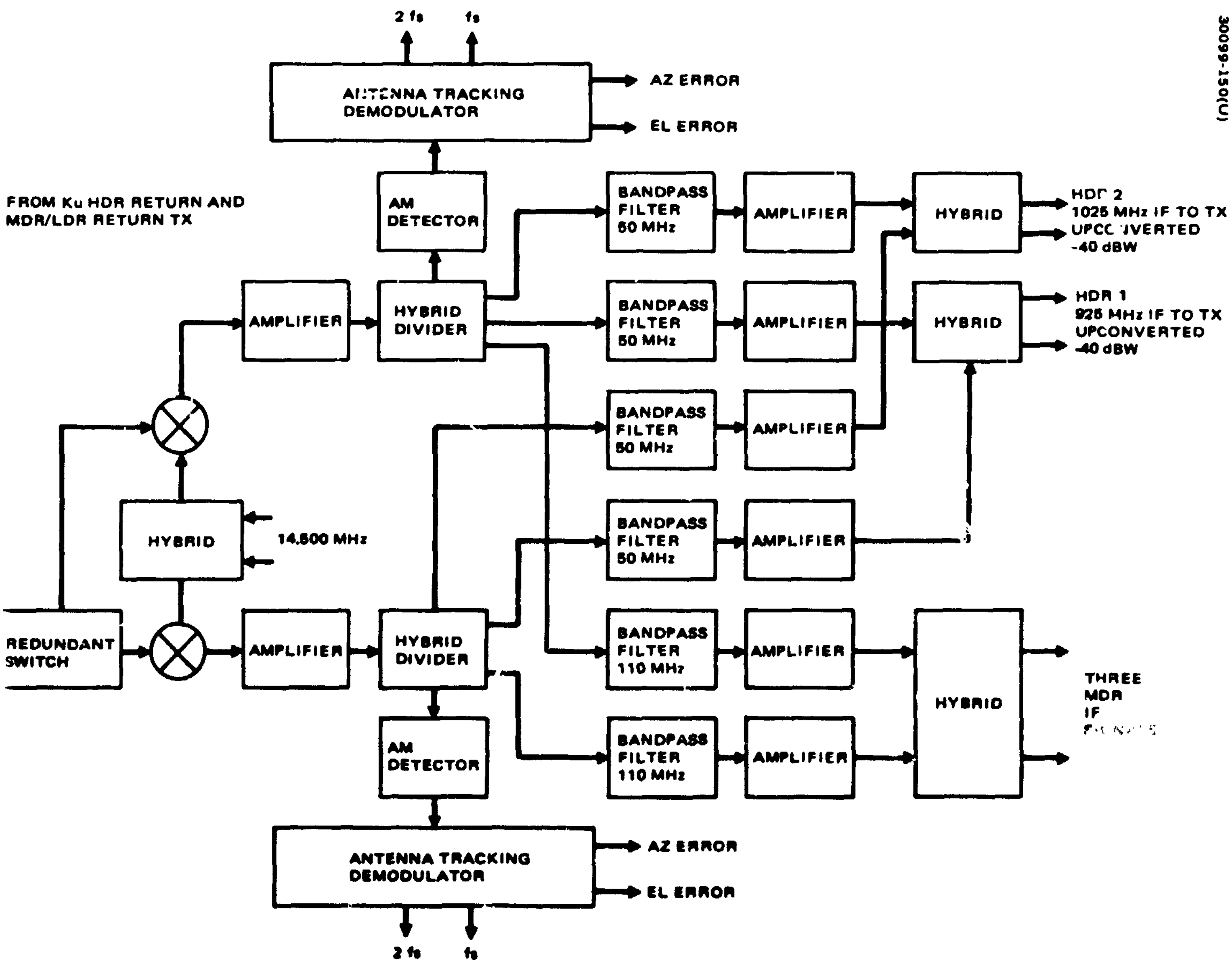


Figure 37. HDR/MDR Forward Link Receiver



rd Link Receiver

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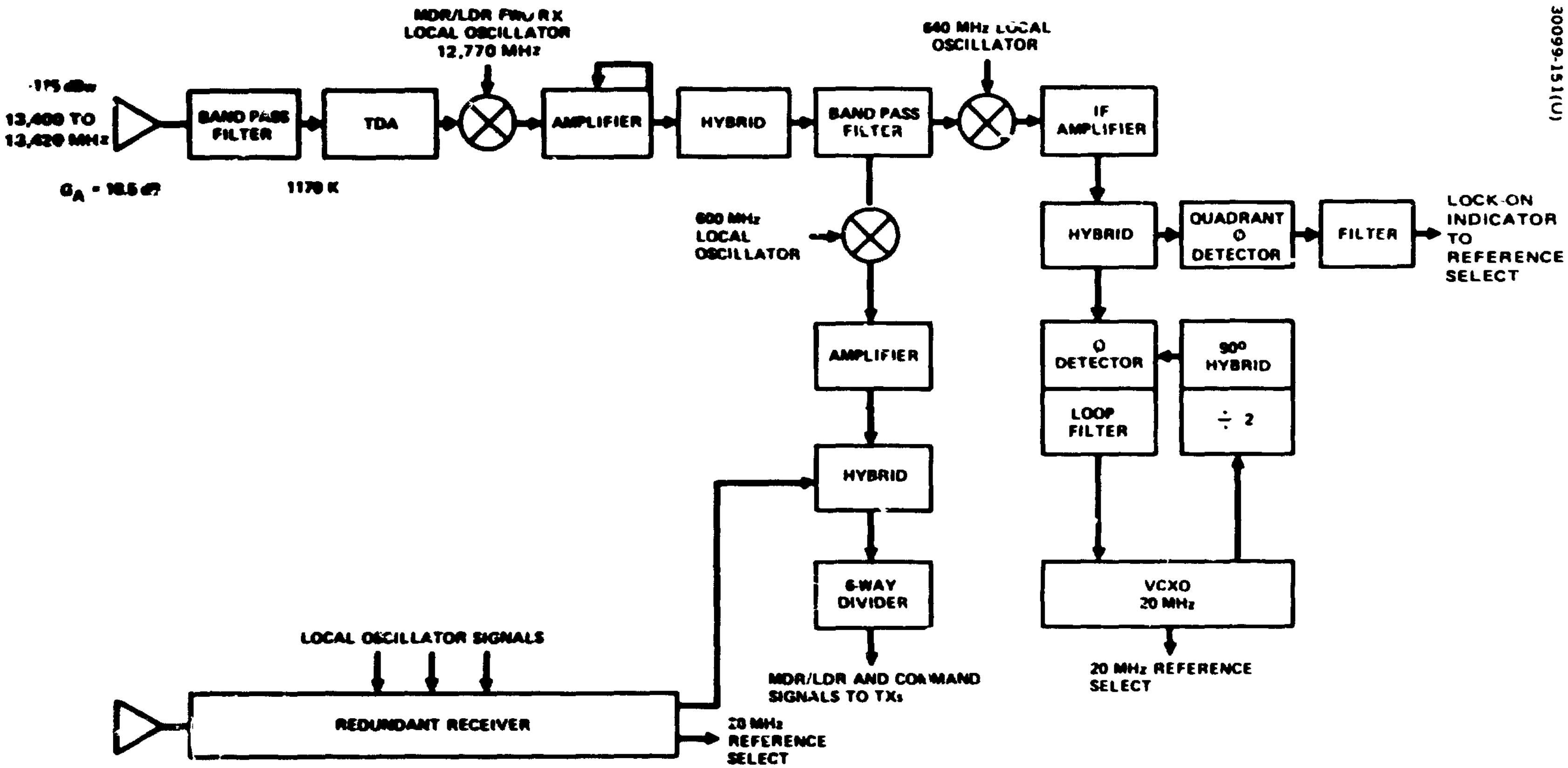

Figure 38. TDRS Command, LDR, and Beacon Receiver

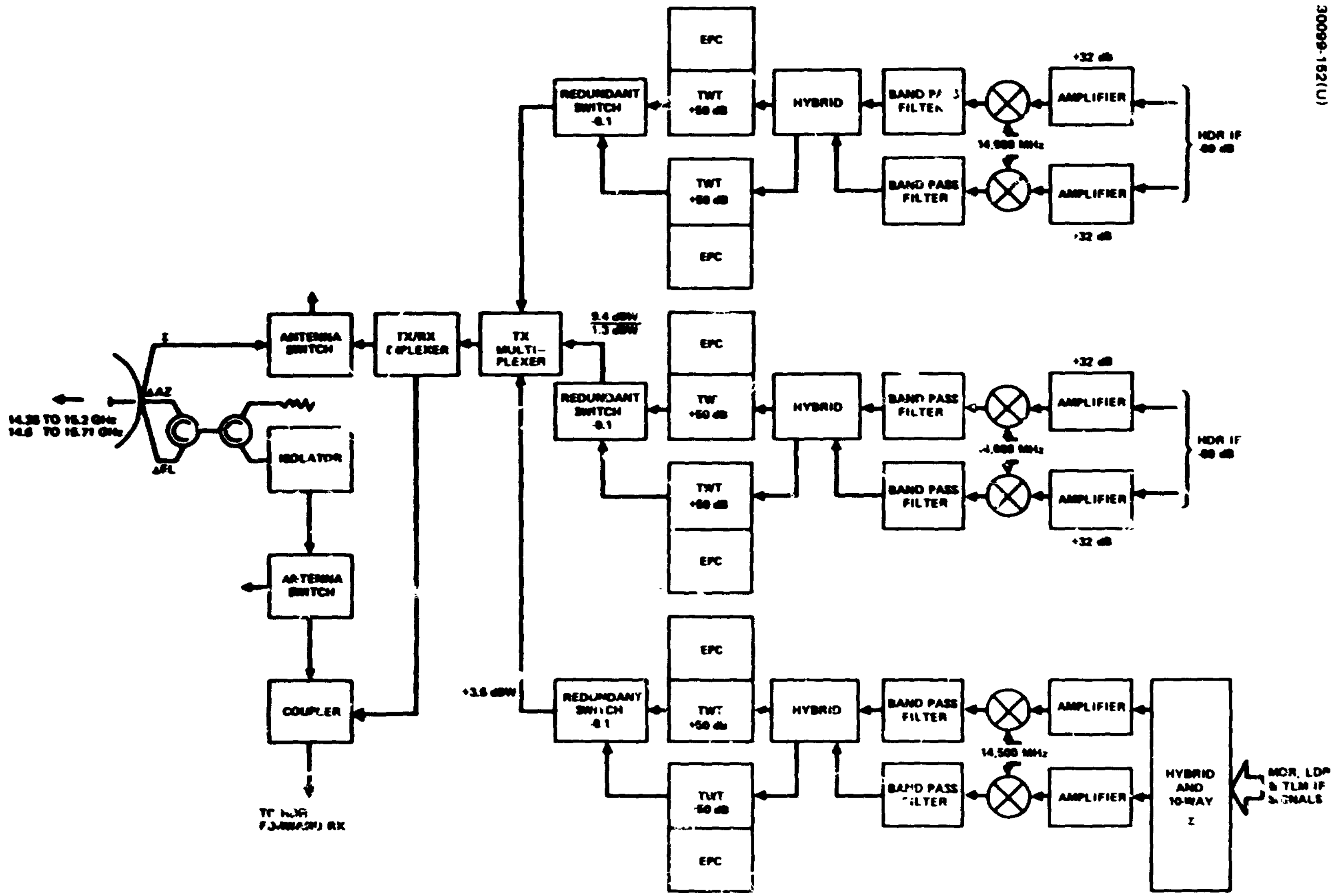

Figure 39. HDR and MDR/LDR Return Link Transmitters and Upconverters

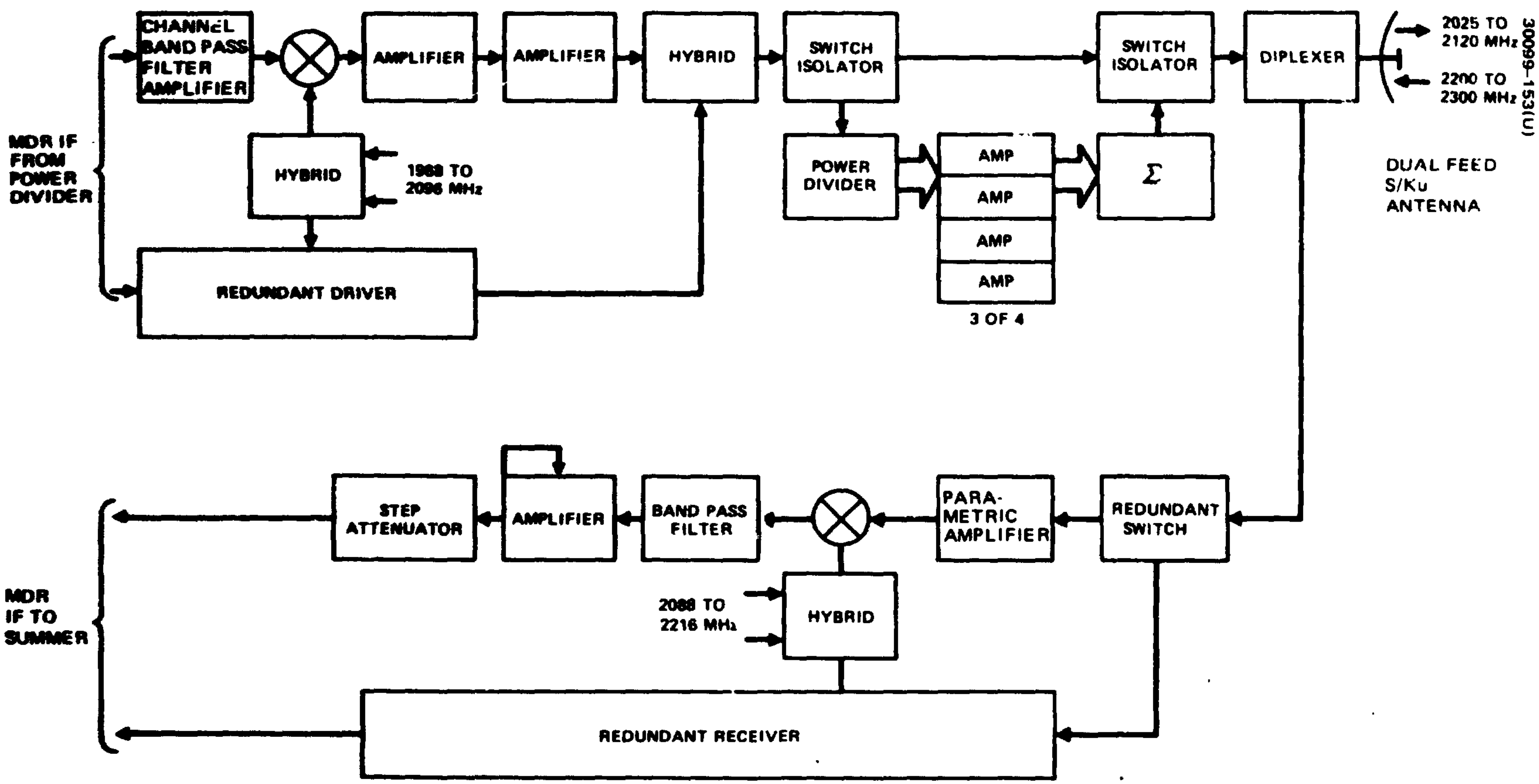

Figure 40. MDR Forward Link Transmitter and MDR Return Link Receiver

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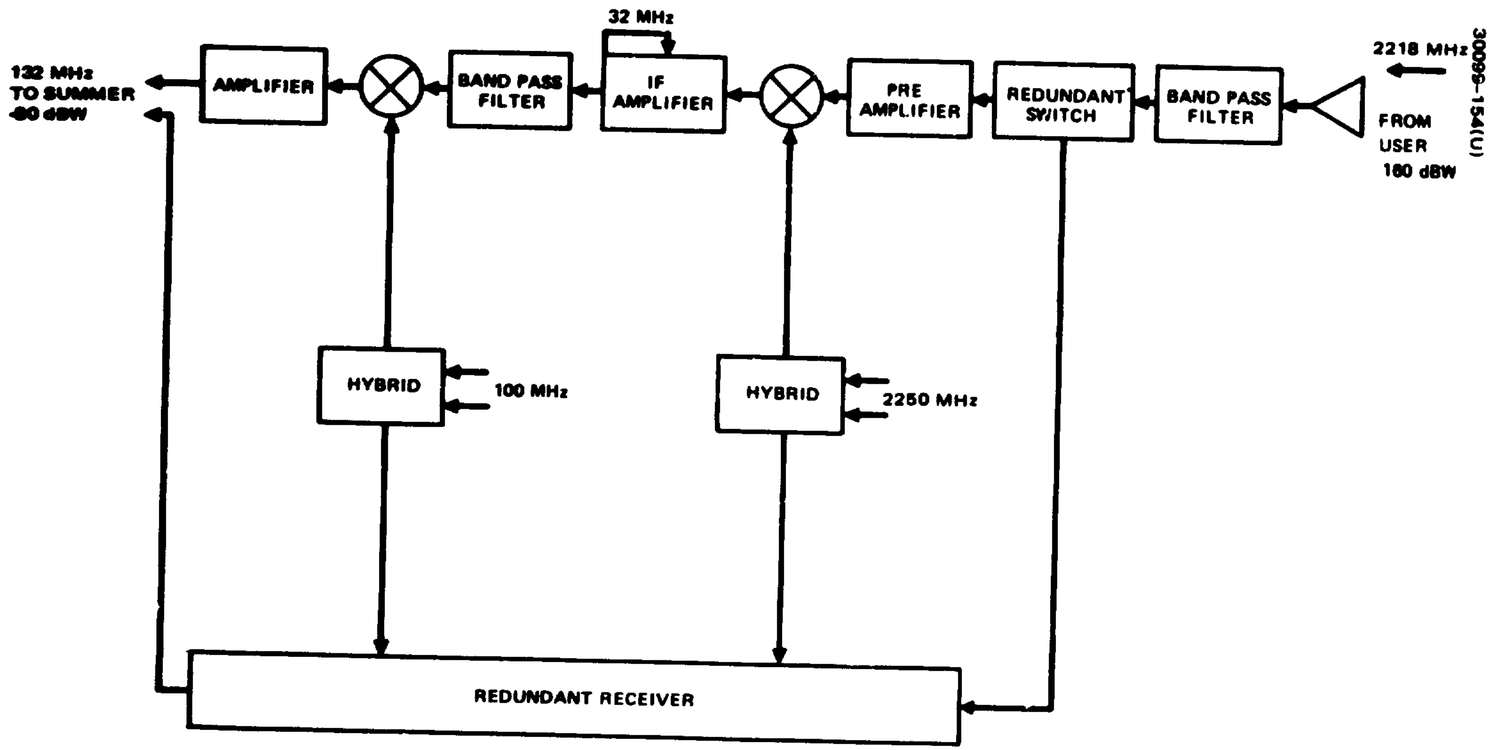

Figure 41. Order Wire Receiver

The order wire function is provided by receiving order wire signals at 2218 MHz and combining the data with the MDR, and LDR if signals for transmission on the Ku band downlink. Figure 41 is a block diagram of the order wire receiver. The order wire receiver is similar to the MDR receiver; however, it has a fixed frequency and narrow bandwidth. The double conversion utilizes mixing frequencies available from the frequency synthesizer to provide the proper IF. The receiver design includes redundancy and applies microstrip transmission techniques in the RF circuits to minimize mass.

TDRS ranging by trilateration is accomplished with an S band solid-state transponder as shown in the block diagram of Figure 42.

The S band ranging transponder is compatible with GRARR frequencies and is designed to transpond ranging data for trilateral ranging with three ground stations. The frequencies selected for TDRS ranging are near the edge of the band to minimize interference and RF filtering problems. It is a crystal transponder, having a self-contained conversion frequency source. The transmitter is completely solid state and the range code received is phase modulated on the carrier by a 222 MHz phase modulator in the transmit multiplier chain. S band microstrip techniques are used throughout to minimize the mass.

4.3.1.4 VHF and UHF Repeater Units

The TDRS LDR service provides voice and command transmissions to at least 20 user spacecraft and voice and telemetry data from 20 users simultaneously. The transmitter power amplifier must provide a 71 watt output per channel or a maximum 142 watts when both command and voice are transmitted simultaneously. Figure 43 is a block diagram of the LDR forward link transmitter.

The LDR forward link transmitter features solid-state driver with redundancy and a final power amplifier using hybrid coupled transistor amplifiers. A command selectable group of four power amplifier outputs is summed by a switched Wilkinson summer to provide the required 71 watt power output at 401 MHz, 142 watts are provided by 8 parallel power amplifiers. The low pass filter at the output attenuates the harmonic and spurious signal outputs from the transmitter. The overall amplifier efficiency is 51 percent and includes regulator losses and 3 percent allowance for space environment and life degradation.

The LDR return link uses a five-element AGIPA antenna to provide RFI rejection.

The LDR receiver is designed to process the two outputs from each of the five AGIPA antenna elements independently through ten channels. The channels are frequency-translated to ten Ku band frequencies for transmission to the ground station in the MDR/LDR return link transmitter. High reliability is achieved by complete redundancy of all channels. This is

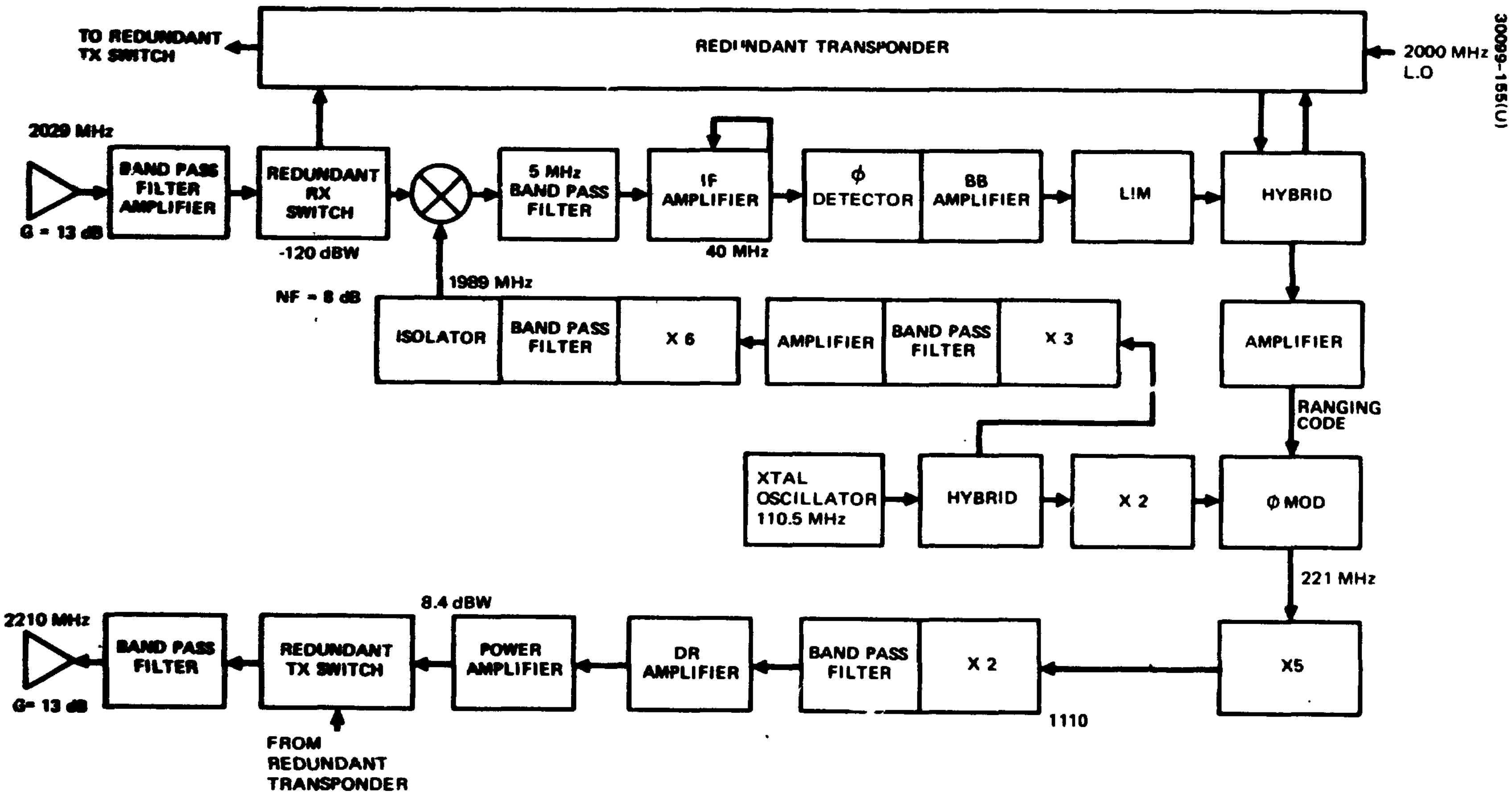

Figure 42. S Band Ranging Transponder

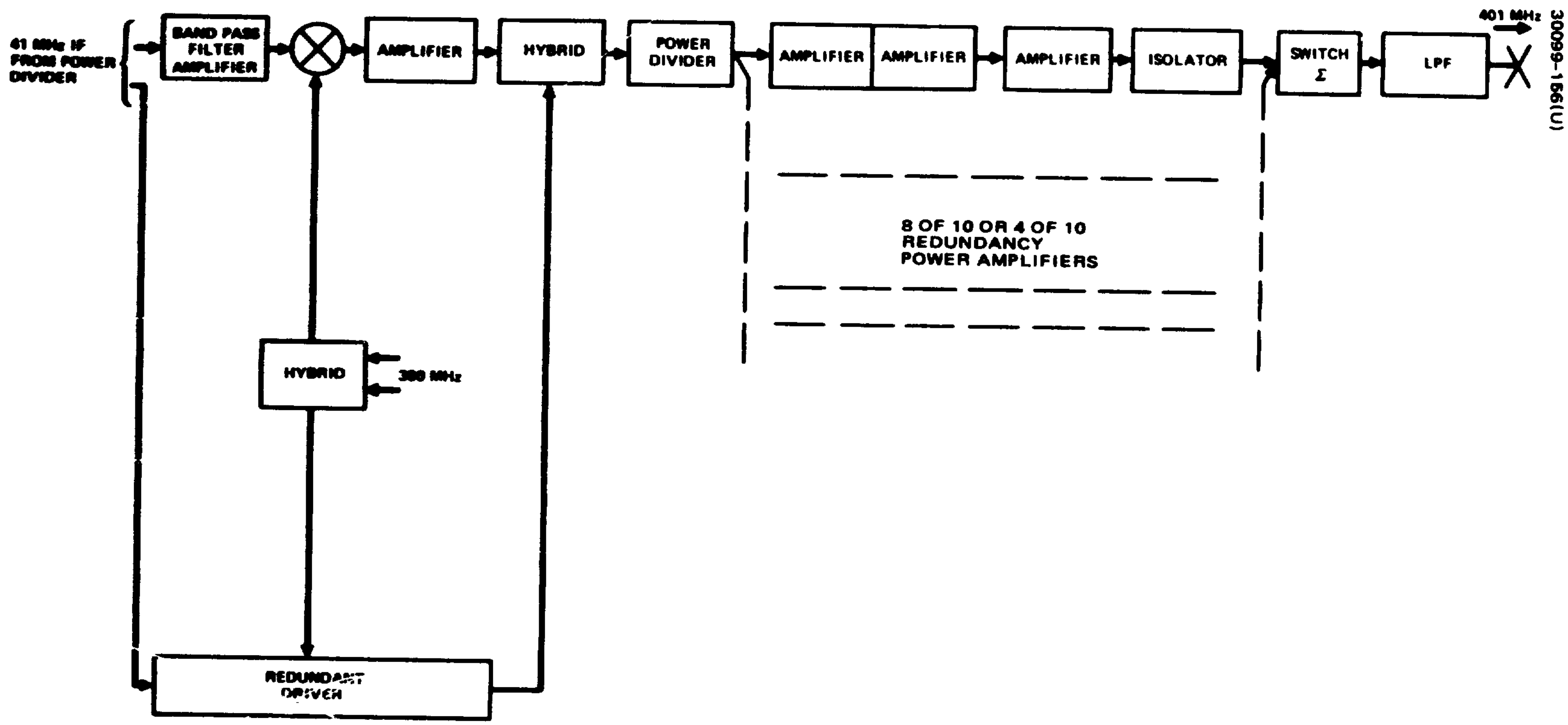

Figure 43. LDR Forward Link Transmitter

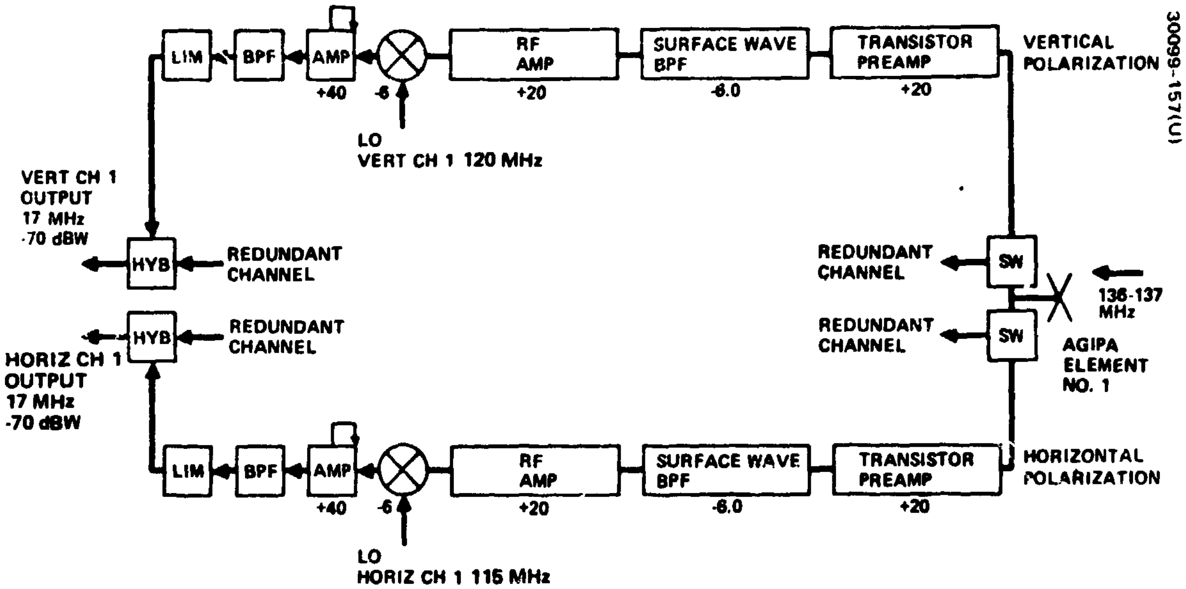

Figure 44. Redundant VHF Receiver

illustrated in Figure 44 which also shows the transistor preamplifier and the acoustic surface wave RF bandpass filter. The IF channel filter bank is made up of monolithic crystal filters. The outputs are summed and upconverted to frequencies between 120 and 165 MHz. The ten channels are evenly spaced over this band with 5 MHz between center frequencies. Specific unequal frequency spacing may become necessary during detailed design to minimize intermodulation products. The LDR receiver contains an internal local oscillator frequency source to simplify the distribution of the many local oscillator signals required for the ten-channel receiver. A 5 MHz harmonic generator, frequency multipliers, and amplifiers are combined to provide the ten local oscillator inputs between 85 and 130 MHz.

4.3.1.5 Frequency Synthesizer

The frequency synthesizer provides the necessary conversion frequencies for each of the receivers and transmitters in the TDRS communication subsystem. This requires a total of 14 frequencies to be derived from a stable crystal oscillator reference source. The primary reference source is a 20 MHz voltage-controlled oscillator that is phase locked to an incoming pilot tone through the Ku band CMD/LDR receiver. When phase locked to the pilot tone, the reference oscillator becomes a coherent frequency reference source. A secondary or standby reference source is also provided for use when the primary reference source is not phase locked to the incoming pilot tone. The secondary reference source is a quartz crystal master oscillator, temperature controlled to maintain the required stability. The 14 output frequencies are generated by several solid-state multiplier chains. Three pairs of S band outputs are programmable in 1 MHz steps to provide repeater flexibility of user spacecraft interface frequencies.

All of the frequency synthesizer circuitry is straightforward in design. Extensive use of large-scale integration circuits will be made. Frequency divider integrated circuit breadboards developed for other space programs are directly applicable for this unit. Compact VCXO modules for the phase lock loop oscillators as required in the frequency synthesizer have been space-qualified. Wherever practical, monolithic crystal filters will be used to minimize circuit element mass, such as in the lower IF channel filters.

The dual regulator used for the frequency synthesizer, typical of those used throughout the repeater, is a series dissipative regulator. This regulator design has exhibited excellent in-orbit performance and reliability on the ATS and Intelsat IV satellites. The regulators are designed with discrete component construction; however, the design is adaptable to hybrid microcircuit techniques. All TDRS regulators will have the same basic circuit topology with only small differences in command buffer logic.

4.3.2 Telemetry, Tracking, and Command

The major tasks of the telemetry, tracking, and command subsystem are to:

1) Monitor and relay to a ground control station all spacecraft analog and status data required for mission management and control, power management, repeater gain adjustments, etc.

2) Provide satellite range information at any phase of its mission.

Telemetry, tracking, and command performance characteristics are listed in Table 22. The TT&C subsystem is illustrated in Figure 45. All units are fully redundant and cross-strapped. A command transmission consists of a microwave carrier modulated by a sequence of tones at three discrete frequencies, designated 1, 0, and execute. The tones are amplitude-modulated. The demodulated output of the Ku band receiver and the S band command receiver drive both the despun and spinning decoders. The selection of the executing decoder is by unique decoder address. Command verification is provided by telemetry readout of the command register before sending the execution tone (Figure 46). A functional description of the spinning and despun decoder is shown in Figure 47.

Two receiver sequencers sample the two S band and the two Ku band receiver outputs to select one that has a suitable output signal. The output of the first stage of each filter goes to the AM detector where the two signals are summed and the composite signal is full-wave rectified and fed to a clock pulse generator which contains a narrow bandpass filter tuned to the 128 Hz bit rate. The output of the 128 Hz bandpass filter is the demodulated AM, a 128 Hz sine wave with an amplitude proportional to the signal strength of the received AM-FSK signal. The 128 Hz sine wave is fed to a hard limiter in the squelch circuit. The squelch circuit puts out a signal to enable the decoder processing when the input signal exceeds a preset threshold

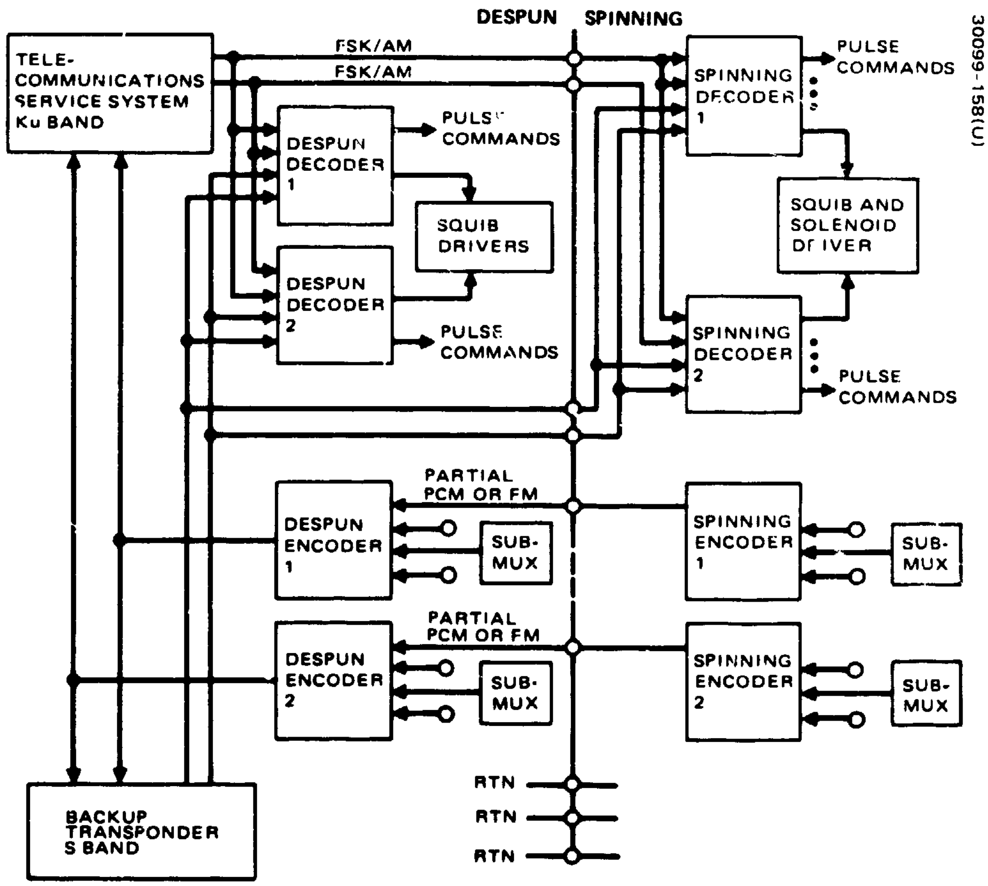

Figure 45. Tracking, Telemetry, and Command Subsystem

level. The 128 Hz sine wave is also fed to the clock pulse generator which generates the clock signals to drive the remainder of the demodulator. In addition to its command outputs, each decoder provides readout of its register (command verification) and the envelope of all execute tone pulses.

A spinning squib and solenoid driver unit generates suitable signals for firing the BAPTA clamp release, apogee motor squibs, and for energizing the latching valve and thruster solenoids. A despun squib driver unit generates signals for antenna deployment. There are four squib drivers and ten solenoid drivers.

Signal and word format of the demodulated command from a receiver consists of a sequence of 1, 0, and execute tone pulses. These are arranged as shown in Figure 46. For convenience, the 1 and 0 pulses will be referred to as bits, as they convey binary information to the decoder logic circuit. The introduction portion of the command word consists of at least 16 0-bits followed by a 1-bit. This resets the decoder registers and logic; the decoder is then able to process the remainder of the command word. The next 8 bits

TABLE 22. TELEMETRY AND COMMAND PERFORMANCE CHARACTERISTICS

TELEMETRY – INTELSAT IV TYPE	
PCM Mode	
Word length	8 bits (11 words subcommutated)
Frame length	64 words (11 words subcommutated)
Analog words	110 words (8 subcommutations)
Digital words	31 total (8 subcommutations)
Bit rate	1000 bps
Code type output	Manchester
FM Mode (attitude data)	
Subcarrier frequency	14.5 kHz
Data type	Real time pulses
Modulation	FM
Data transmitted	1) Sun pulses 2) North earth pulses 3) South earth pulses 4) Execute receipt
COMMAND – INTELSAT IV TYPE, MODIFIED	
Tones	1, 0, and execute
Input signal	FSK/AM
Bit rate	128 bps
Command capacity, maximum	255 despun, 127 spinning
Command verification	Telemetry
Command execution	Real time
Execution synchronization	Sun or earth pulses
Maximum command rate	Approximately 4 per second

COMMAND GENERATOR CONTROL	FUNCTION PERFORMED	TONE	CODE	DURATION
ACTUATE XMIT				
	INTRODUCTION (CLEAR)	0	16 BITS	258 ms
		1	1 BIT	
	DECODER ADDRESS	0 AND 1	6 BITS	
		1	2 BITS	
	COMMAND	0 AND 1	8 BITS	
READ DECODER REGISTERS	COMMAND VERIFICATION VIA TELEMETRY			
ACTUATE EXECUTE				
	COMMAND EXECUTE	EXECUTE TONE	AS REQUIRED	VARIABLE TIME (40 ms FOR STANDARD SINGLE COMMAND)
ACTUATE CLEAR				
	CLEAR THE DECODER REGISTERS	0	16 BITS	133 ms
		1	1 BIT	

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Figure 46. Command Format

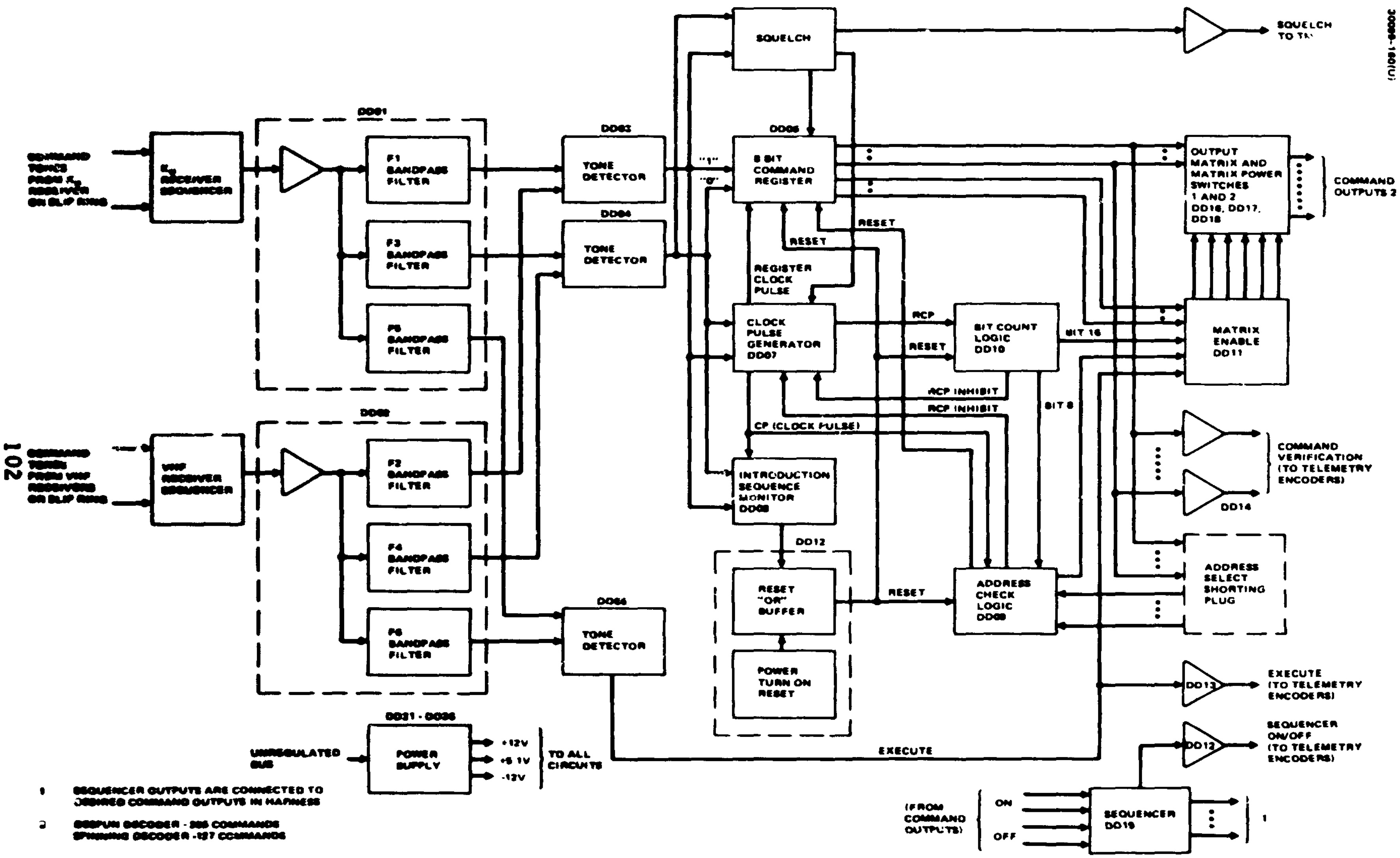

Figure 47. Despun or Spinning Decoder Block Diagram

comprise the address portion of the command word. In order to take advantage of the full command capability of the decoder design, spinning decoders have an address that is different from the despun decoders. The first 6 provide the coding for digital addresses. The address words are separated by a minimum Hamming distance of 2, so that a single error in the transmission or reception of a decoder address will not result in the successful addressing of a wrong decoder. The last 2 bits are both 1's, which ensures that the introduction sequence will never be repeated within the command word.

The command itself consists of 8 bits. The 8 command bits are entered into a storage register for verification via telemetry. Once a command word is entered into storage, further processing of data bits is inhibited and an introduction format must be sent to clear the register. Upon receipt of the execute tone, a coincident pulse will occur on the decoder output line corresponding to the stored command. Execute tone pulses can be sent for as long or as frequently as required. After the command has been executed, the commanding ground station resets and clears the decoder by repeating the introduction.

The telemetry subsystem, in the primary mode of operation, provides two independent channels (Figure 45) transmitting on separate carrier frequencies with separate telemetry encoders for each channel. Two modes of data processing are used: PCM and FM real time.

The PCM mode is used for all attitude, thermal, power, and status information, including command verification. In the PCM mode, the spinning encoder receives, processes, and formats data originating on the spinning portion of the satellite. The output, which is connected across the spinning/despun interface via slip rings, is an 8 kHz biphase waveform from which a despun encoder recovers the nonreturn to zero (NRZ-L) bit stream and derives a coherent clock. The despun encoder gathers and processes data originating in the despun portion. It alternates its bit stream word by word with the spinning encoder bit stream, then converts the composite NRZ-L bit stream to a Manchester code format. The converted stream is used for phase modulating a Ku band carrier within the telecommunication repeater on the despun side and modulates the backup S band transmitter on the spinning side.

To accommodate the increased telemetry requirements for the Space Shuttle launched TDRS spacecraft, the baseline Intelsat IV telemetry subsystem has been modified to include some subcommutated channels. In the main frame, one digital and four analog words on the spinning side and two digital and four analog words on the despun side are subcommutated. To accomplish this, the central encoders are modified to incorporate the additional timing and logic and a new remote submultiplexer unit will be designed to provide the additional channels. (See Figure 45.)

The FM real time mode is used for real time attitude pulses (sun sensor pulses, earth sensor pulses, platform ind . pulses, and command execute pulses). The occurrence of a pulse coherently switches the frequency of an IRIG channel 13 subcarrier oscillator from its pilot tone to a different frequency, depending on the kind of pulse present. The output is connected via a slip ring to the despun encoder, the output of which phase modulates the Ku and S band telemetry transmitters.

The functional design of the spinning encoder and the despun encoder is illustrated in Figures 48, 49, and 50.

Mass, power, and dimensional data for components of the telemetry subsystem are listed in Table 23. Lists of telemetry and command requirements are provided in Tables 24 and 25, respectively.

TABLE 23. TELEMETRY AND COMMAND COMPONENT PHYSICAL CHARACTERISTICS

Unit	Number per Spacecraft	Mass per Spacecraft, kg	28 Volt Bus: Power Per Unit, watts	28 Volt Bus: Spacecraft Standby Power, watts	Size, cm: Width	Size, cm: Length	Size, cm: Height	Program Identification
Despun								
Decoder	2	2.7	0.9/1.8 (2)	1 8	14 7	22 6 (1)	6.9	HS 312
Encoder	2	4.2	4.0		14 7	22 6 (1)	6.9	HS 312
Squib driver	1	2.5	–	–	14 7	15 2	3.6	MC
Spun								
Decoder	2	2.7	0.9/1.8 (2)	1 8	14 7	31 0 (1)	6 9	HS 312
Encoder	2	5.0	5.0	5.0	14.7	31.0 (1)	6 9	HS 312 Mod
Solenoid and squib driver	1	0.9	–	–	14.7	34.3	3 6	HS 320
Latching valve – heater driver	1	0.5	–	–	6.6	8.9	7 4	–

NOTES: (1) Stackable units.
(2) Standby/execute.

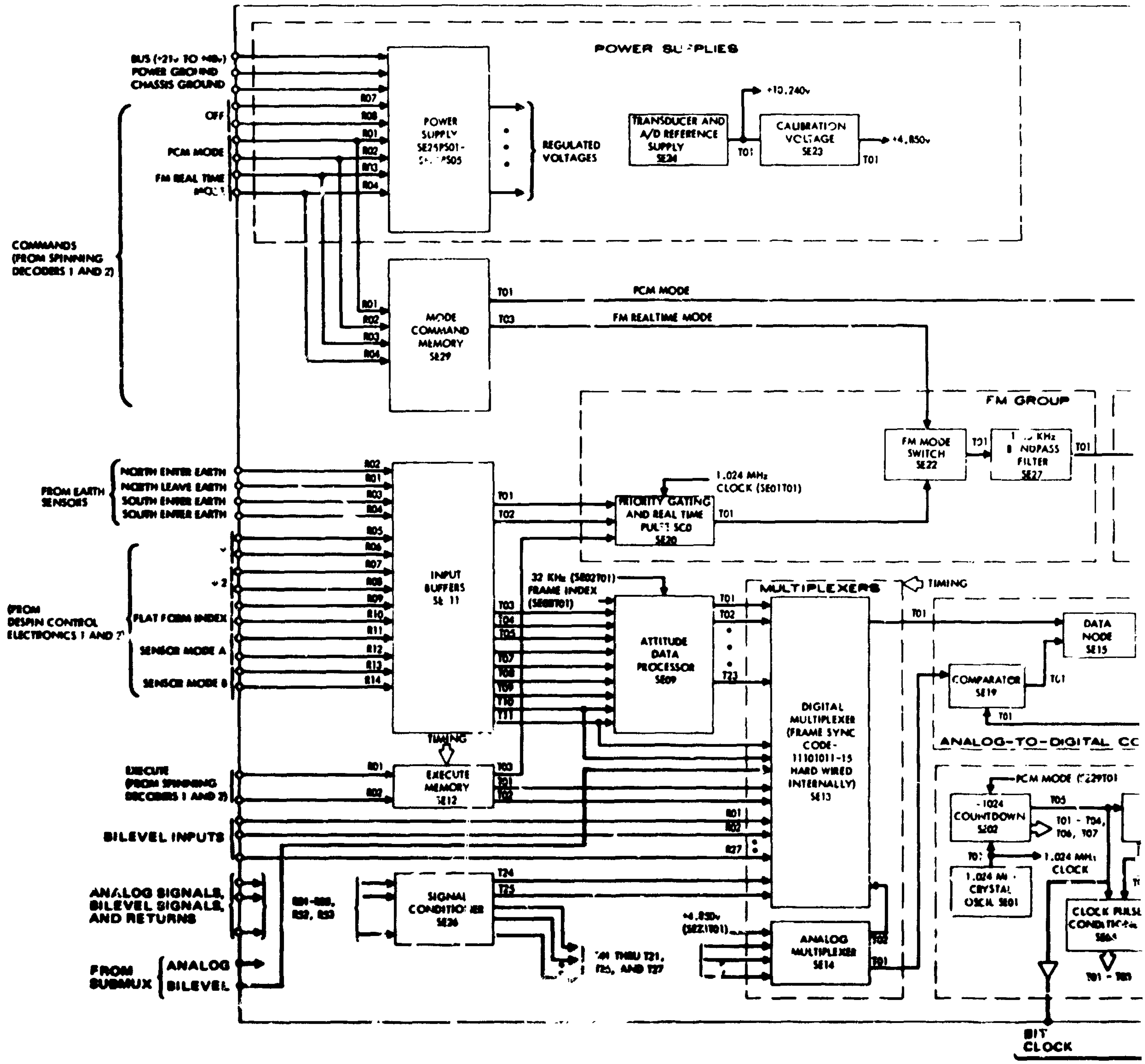

Figure 4- Spinning Encoder Block Diagram

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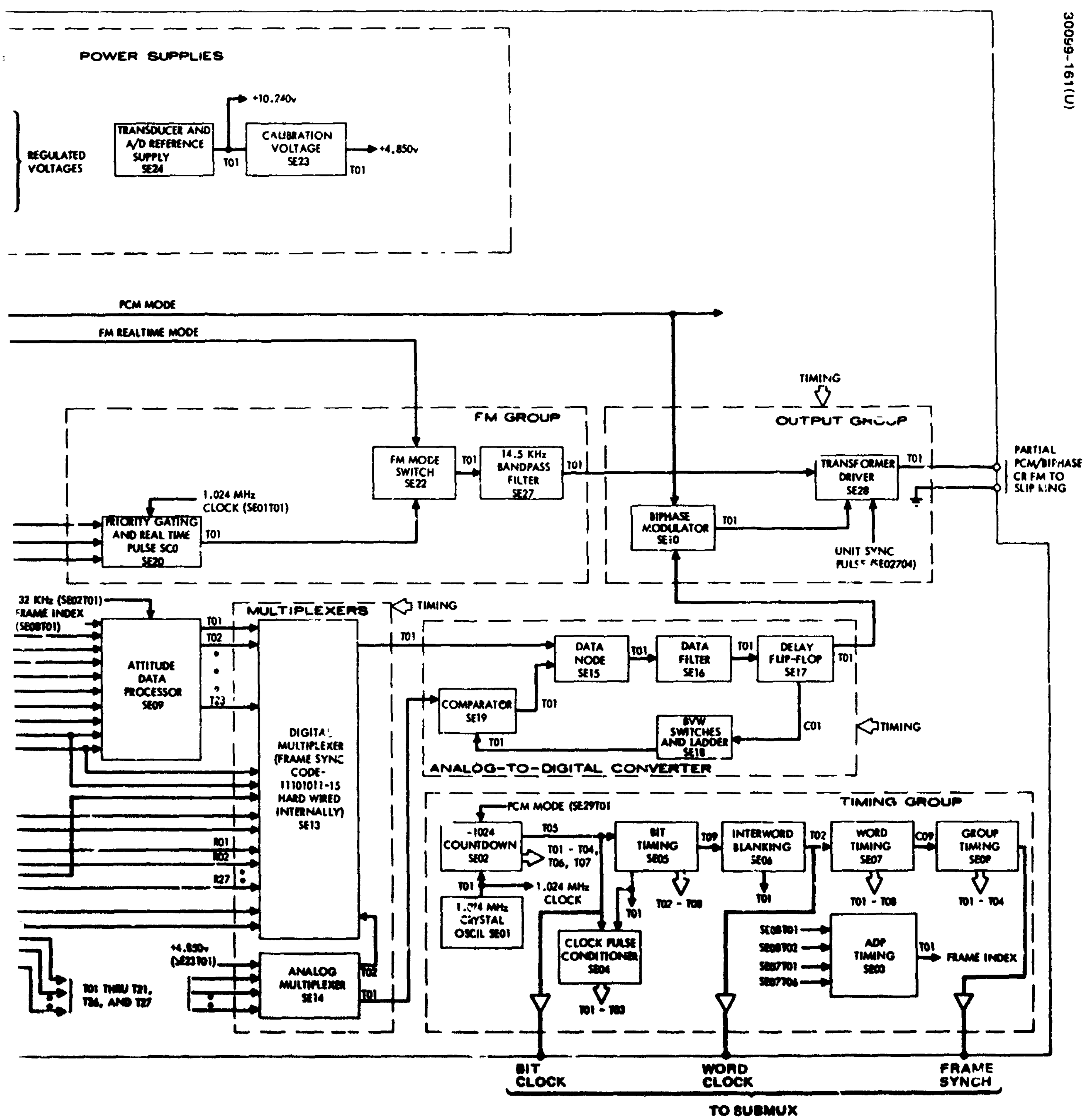

r Block Diagram

FOLDOUT FRAME 2

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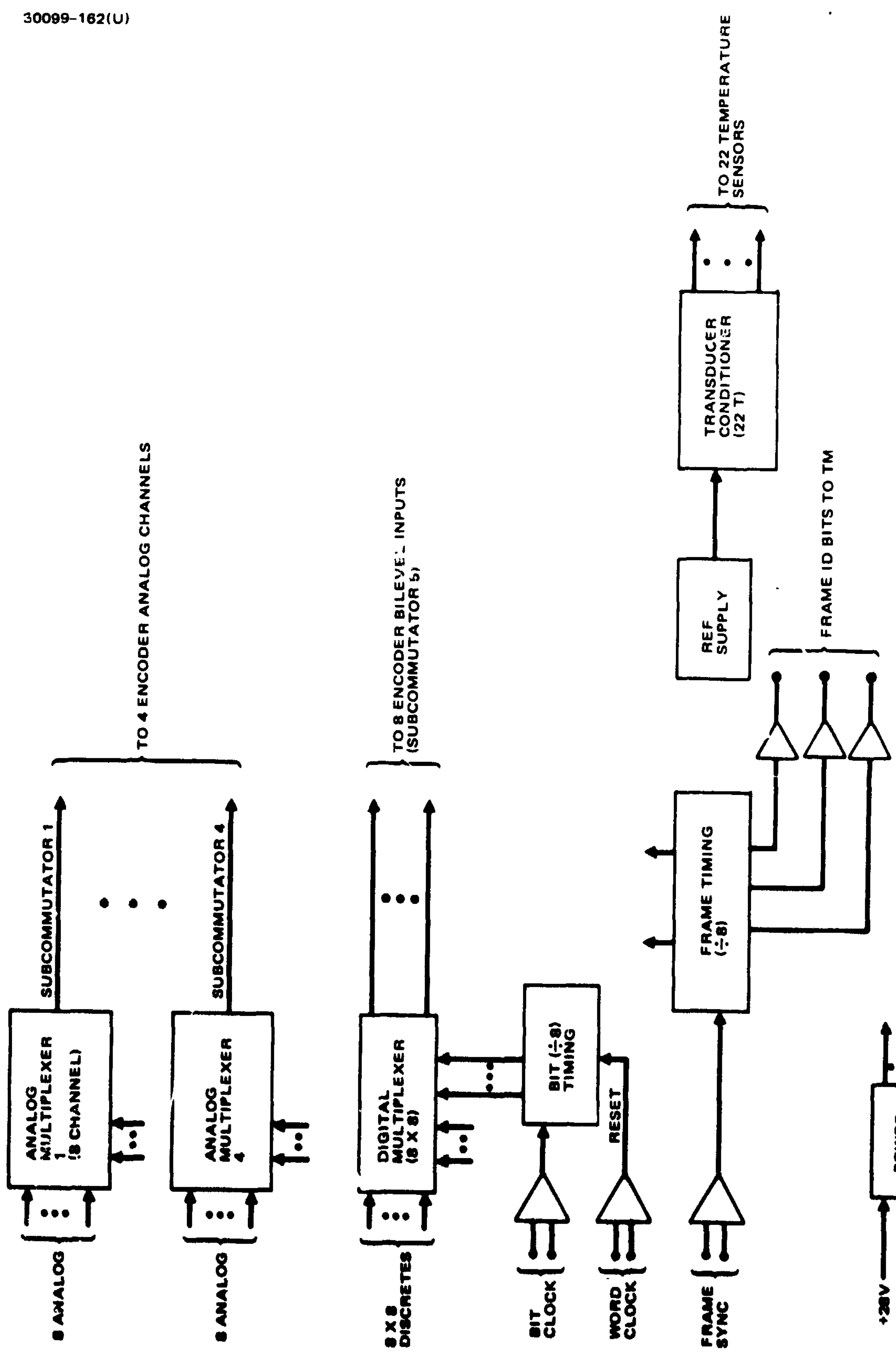


Figure 49. Submultiplexer Unit Block Diagram

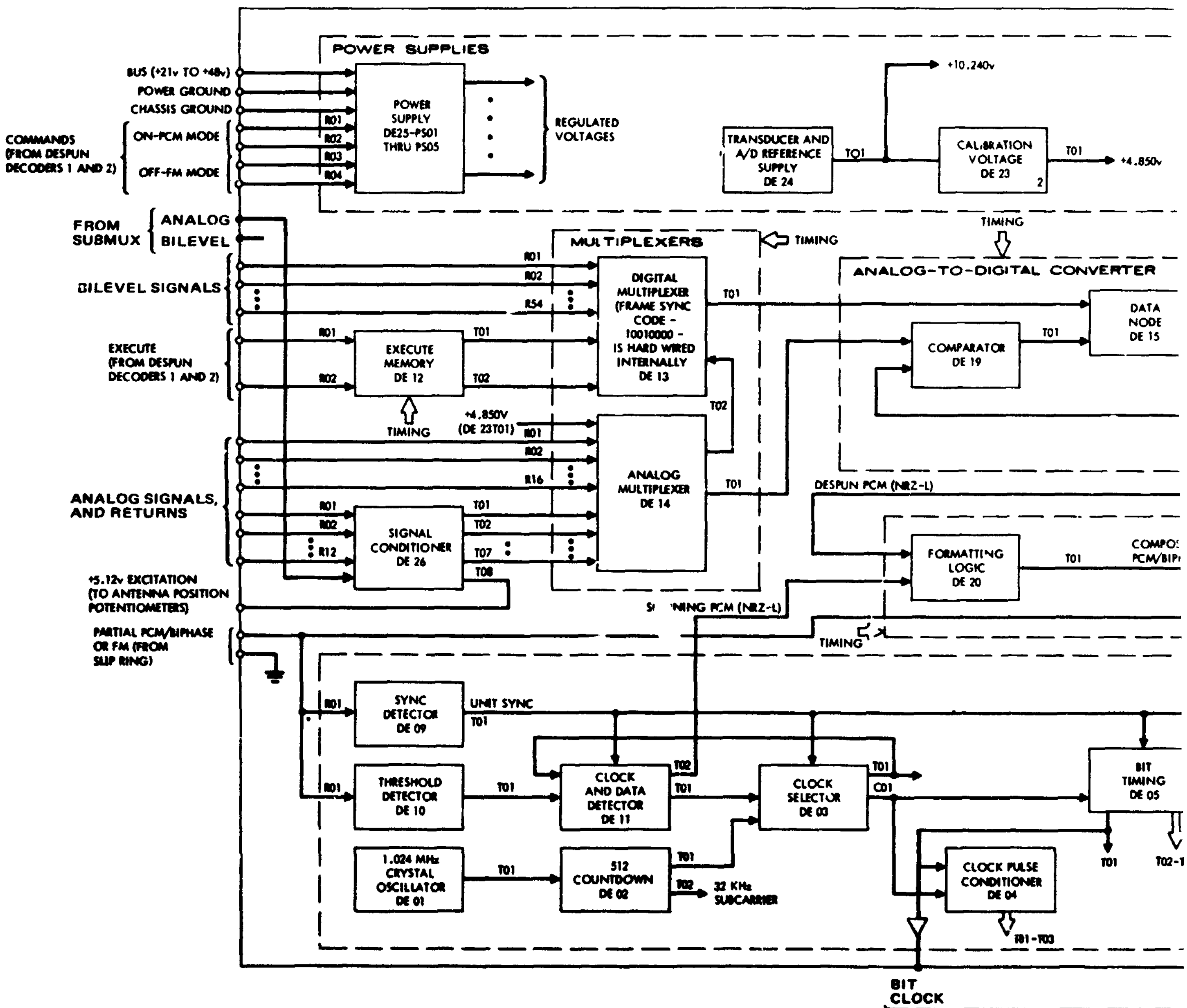
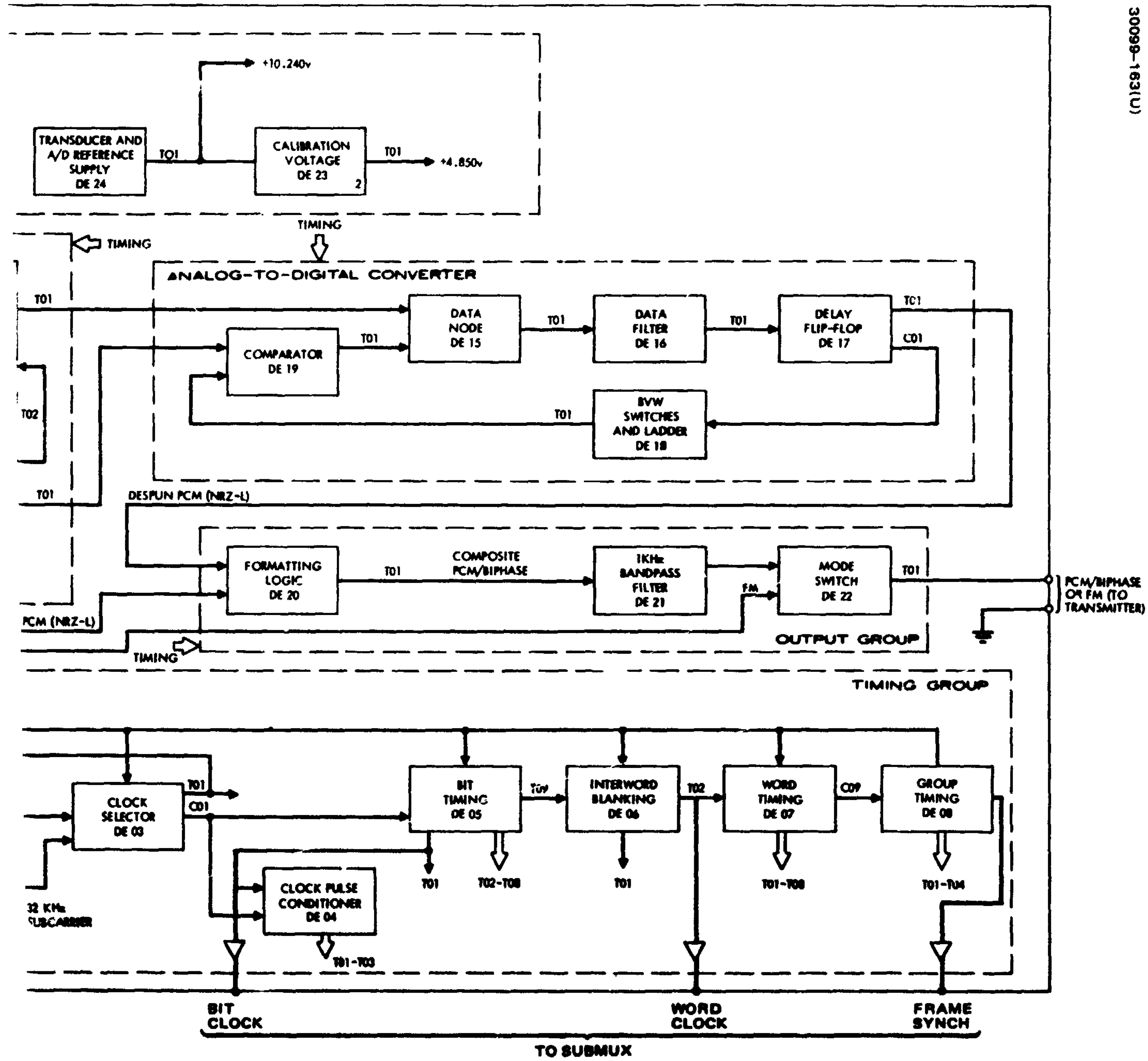


Figure 50. Despun Encoder Block Diagram

D



ram

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TABLE 24. TELEMETRY CHANNEL ASSIGNMENTS

Main Frame Word	Spinning	Despun
0	Frame sync	
1		Frame sync
2	Decoder 1 command verify	
3		Decoder 1 command verify
4	Decoder 2 command verify	
5		Decoder 2 command verify
6	Status word 6	
7		Status word 7
8	Subcommutation (digital)	
9		Status word 9
10	Attitude determination	
11		Subcommutation (digital)
12	Attitude determination	
13		Subcommutation (digital)
14	Attitude determination	
15		Status word 15
16	Subcommutation	
17		Subcommutation
18	Subcommutation	
19		Subcommutation
20	Subcommutation	
21		Subcommutation
22	Subcommutation	
23		Subcommutation
24	Telemetry calibration	
25		Bus voltage
26	Bus current	

Table 24 (continued)

Main Frame Word	Spinning	Despun
27		Antenna A azimuth**
28	Bus voltage	
29		Antenna A elevation**
30	Despin position torque command*	
31		Antenna B azimuth**
32	Motor torque command*	
33		Antenna B elevation**
34	Motor 1 current	
35		Antenna C azimuth**
36	Motor 2 current	
37		Antenna C elevation**
38	Spare	
39		Antenna D azimuth**
40	Spare	
41		Antenna D elevation**
42	Spare	
43		Telemetry calibration
44	Spare	
45		Spare
46	Spare	
47		Spare
48	Spare	
49		Spare
50	Spare	
51		Spare

*Both torque command signals are connected to each encoder via OR circuits, since only one despin control electronic unit is on at a time.

**Digital output increases when antenna steers toward north or west.

Table 24 (continued)

Main Frame Word	Spinning	Despun
52	Spare	
53		Spare
54	Spare	
55		Spare
56	Spare	
57		Spare
58	Spare	
59		Spare
60	Spare	
61		Spare
62	Spare	
63		Spare

Subcommutation Channel

Status Digital Bit Assignment – Spinning

6	–	Status Word 6 (8 bits) Spinning Encoder Bit 1 Spinning decoder 1 execute 2 Spinning decoder 2 execute 3 Spacecraft separation 4 Spinup sequencer 1/2 OFF 5 Sub frame count 6 Sub frame count 7 Sub frame count 8 Spare
8	0	Reaction Control Status Bit 1 Latching valve 1 OPEN/CLOSE 2 Latching valve 2 OPEN/CLOSE 3 Latching valve 3 OPEN/CLOSE 4 Latching valve 4 OPEN/CLOSE 5 Latching valve 5 OPEN/CLOSE 6 Radial valve heater ON 7 Axial valve heater ON 8 Spin valve heaters ON

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
	Status Digital Bit Assignment – Spinning	
	1	Reaction Control and Apogee Motor Status Bit 1 Apogee motor 1 OFF 2 Apogee motor 2 OFF 3 Apogee motor 3 OFF 4 Apogee motor 4 OFF 5 Spinup thrusters 1/2 6 Spare 7 Spare 8 Spare
8	2	TT&C Status Bit 1 Telemetry encoder 1 PCM mode 2 Telemetry encoder 2 PCM mode 3 Telemetry encoder 1 ON (spinning) 4 Telemetry encoder 2 ON (spinning) 5 Telemetry transmitter A ON 6 Telemetry transmitter B ON 7 Spare 8 Spare
	3	Electrical Power Status Bit 1 Trickle charge battery 1 OFF 2 Trickle charge battery 2 OFF 3 Trickle charge battery 3 OFF 4 Trickle charge battery 4 OFF 5 Set charge temperature limit 1 6 Set charge temperature limit 2 7 Set charge temperature limit 3 8 Set charge temperature limit 4
	4	Electrical Power Status Bit 1 Thermal charge limit set override 2 Voltage limiter 1 ON 3 Voltage limiter 2 ON 4 Voltage limiter 3 ON 5 Voltage limiter 4 ON 6 Voltage limiter 5 ON 7 Voltage limiter 6 ON 8 Reconditioning discharge ON

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
Status Digital Bit Assignment – Spinning		
8	5	Controls Status Bit 1 Despin electronics 1 ON 2 Despin electronics 2 ON 3 Motor drive 1 ON 4 Motor drive 2 ON 5 ANC 1 ON 6 ANC 2 ON 7 Motor driver 1 low/high gain 8 Motor driver 2 low/high gain
	6	Controls Status Bit 1 Command limiter ON 2 Interlock enable 3 Rate command latch 1/2 4 Earth sensor 1 OFF 5 Earth sensor 2 OFF 6 Earth sensor 3 OFF
	7	Control Status Bit 1 Select earth sensor 1 2 Select earth sensor 2 3 Select earth sensor 3 4 SCL enable 5 Spare 6 Spare 7 Spare 8 Spare
		Status Word 10 (8 bits) Attitude Determination
10	Code	Measurement — Bit
	t_1	Spin period — 1 2 3 4 5 6 7 8
	t_2	Sync control reference — 0 0 0 1 1 0 0 0
	t_3	Inner sun chord — 0 0 1 1 1 0 0 0
	t_4	Outer sun chord — 0 1 0 0 1 0 0 0
	t_5	North earth chord — 0 1 0 1 1 0 0 0

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
	Status Digital Assignment – Spinning	Status Word 10 (8 bits) Attitude Determination
10 (cont)	Code	Measurement / Bit
	t_6	South earth chord — 0 1 1 0 1 0 0 0
	t_7	Sun-north earth separation — 0 1 1 1 1 0 0 0
	t_8	Sun-south earth separation — 1 0 0 0 1 0 0 0
	t_9	North earth to south earth — 1 0 0 1 1 0 0 0
	t_{10}	Platform pointing — 1 0 1 0 1 0 0 0
		Status Word 12 (8 bits) Attitude Determination
12	–	1/2-16 bit word; bit 1 most significant bit
		Status Word 14 (8 bits) Attitude Determination
14	–	1/2-16 bit word; bit 8 least significant bit of 16 bit word included in status word 12 and 14 and coded in status word 10
16	0	Battery 1 voltage
	1	Battery 2 voltage
	2	Battery 3 voltage
	3	Battery 4 voltage
	4	Battery 1 pack 1 temperature
	5	Battery 1 pack 2 temperature
	6	Battery 2 pack 1 temperature
	7	Battery 2 pack 2 temperature
18	0	Battery 3 pack 1 temperature
	1	Battery 3 pack 2 temperature
	2	Battery 4 pack 1 temperature
	3	Battery 4 pack 2 temperature
	4	Battery 1 charge/discharge current
	5	Battery 2 charge/discharge current
	6	Battery 3 charge/discharge current
	7	Battery 4 charge/discharge current
20	0	Radial jet 1 temperature
	1	Radial jet 2 temperature
	2	Axial jet 1 temperature
	3	Axial jet 2 temperature
	4	Fuel tank 1 temperature
	5	Fuel tank 2 temperature
	6	Hydrazine 1 pressure
	7	Hydrazine 2 pressure

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
Status Digital Assignment – Spinning		
22	0	BAPTA temperature 1
	1	BAPTA temperature 2
	2	Apogee motor temperature 1
	3	Apogee motor temperature 2
	4	Sunshield temperature 1
	5	Sunshield temperature 2
	6	Solar panel temperature 1
	7	Solar panel temperature 2
		Status Word 7 (8 bits) Despun Encoder
7		Bit
		1 Despun decoder 1 execute
		2 Despun decoder 2 execute
		3 Sub frame count
		4 Sub frame count
		5 Sub frame count
		6 Spare
		7 Spare
		8 Spare
9		Status Word 9 (8 bits) Despun Encoder
		Bit
		1 Spare
		2 Spare
		3 Spare
		4 Spare
		5 Spare
		6 Spare
		7 Spare
		8 Spare
11	0	Communication Status
		Bit
		1 Ku band receiver CMD/LDR forward A ON
		2 Ku band receiver CMD/LDR forward B ON
		3 Ku band receiver MDR/HDR forward A ON
		4 Ku band receiver MDR/HDR forward B ON
		5 Antenna tracking modulator driver select A/B (HDR/MDR forward)
		6 Ku band receiver HDR return 1 A ON
		7 Ku band receiver HDR return 1 B ON
		8 Antenna tracking modulator driver select A/B (HDR return 1)

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
	1	Communication Status Bit 1 Ku band receiver HDR return 2 A ON 2 Ku band receiver HDR return 2 B ON 3 Antenna tracking modulator driver select A/B (HDR return 2) 4 Ku band receiver HDR return 1 bandwidth select 5 Ku band receiver HDR return 1 bandwidth select 6 Ku band receiver HDR return 2 bandwidth select 7 Ku band receiver HDR return 2 bandwidth select 8 Ku band transmitter HDR return 1 A ON
11	2	Communication Status Bit 1 Ku band transmitter HDR return 1 B ON 2 Ku band transmitter HDR return 1 TWT select 3 Ku band transmitter HDR return 2 A ON 4 Ku band transmitter HDR return 2 B ON 5 Ku band transmitter HDR return 2 TWT select 6 Ku band transmitter MDR/LDR A ON 7 Ku band transmitter MDR/LDR B ON 8 Ku band transmitter MDR/LDR TWT select
	3	Communication Status Bit 1 Ku band transmitter HDR forward 1 A ON 2 Ku band transmitter HDR forward 1 B ON 3 Ku band transmitter HDR forward 1 TWT select 4 Ku band transmitter HDR forward 2 A ON 5 Ku band transmitter HDR forward 2 B ON 6 Ku band transmitter HDR forward 2 TWT select 7 UHF transmitter driver A ON 8 UHF transmitter driver B ON

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
	4	Communication Status Bit 1 UHF power amplifier 1 ON 2 UHF power amplifier 2 ON 3 UHF power amplifier 3 ON 4 UHF power amplifier 4 ON 5 UHF power amplifier 5 ON 6 UHF power amplifier 6 ON 7 UHF power amplifier 7 ON 8 UHF power amplifier 8 ON
11	5	Communication Status Bit 1 UHF power amplifier 9 ON 2 UHF power amplifier 10 ON 3 VHF horizontal receiver 1 A ON 4 VHF horizontal receiver 1 B ON 5 VHF horizontal receiver 2 A ON 6 VHF horizontal receiver 2 B ON 7 VHF horizontal receiver 3 A ON 8 VHF horizontal receiver 3 B ON
	6	Communication Status Bit 1 VHF horizontal receiver 4 A ON 2 VHF horizontal receiver 4 B ON 3 VHF horizontal receiver 5 A ON 4 VHF horizontal receiver 5 B ON 5 VHF vertical receiver 1 A ON 6 VHF vertical receiver 1 B ON 7 VHF vertical receiver 2 A ON 8 VHF vertical receiver 2 B ON
	7	Communication Status Bit 1 VHF vertical receiver 3 A ON 2 VHF vertical receiver 3 B ON 3 VHF vertical receiver 4 A ON 4 VHF vertical receiver 4 B ON 5 VHF vertical receiver 5 A ON 6 VHF vertical receiver 5 B ON 7 VHF receiver select up converter 8 VHF receiver frequency source select

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
13	0	Communication Status Bit 1 Order wire receiver A ON 2 Order wire receiver B ON 3 S band transponder A ON 4 S band transponder B ON 5 S band transmitter 1 A ON 6 S band transmitter 1 B ON 7 S band transmitter 2 A ON 8 S band transmitter 2 B ON
	1	Communication Status Bit 1 S band transmitter 3 A ON 2 S band transmitter 3 B ON 3 S band transmitter 1 high/low select 4 S band transmitter 2 high/low select 5 S band transmitter 3 high/low select 6 S band receiver 1 A ON 7 S band receiver 1 B ON 8 S band receiver 2 A ON
	2	Communication Status Bit 1 S band receiver 2 B ON 2 S band receiver 3 A ON 3 S band receiver 3 B ON 4 S band MDR receiver 1 step attenuator IN/OUT 5 S band MDR receiver 2 step attenuator IN/OUT 6 S band MDR receiver 3 step attenuator IN/OUT 7 Telemetry encoder 1 ON 8 Telemetry encoder 2 ON
13	3	Deployment Status Bit 1 Release support arm Ku band antenna 1 2 Release support arm S/Ku band antenna 2 3 Release center support S/Ku band antenna 3/4

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
13 (cont)	3	**Deployment Status** Bit (cont) 4 Release S/Ku band antenna 3 arm 5 Release S/Ku band antenna 4 arm 6 Release UHF antenna arm 7 Release Astromast stowage lock 8 Release VHF antenna element 1-4 arms
	4	**Deployment Status** Bit 1 Release VHF antenna element 5 arm 2 Release VHF element 1 from support arm 3 Release VHF element 2 from support arm 4 Release VHF element 3 from support arm 5 Release VHF element 4 from support arm 6 Release VHF element 5 from support arm 7 Release Ku band antenna 1 from support arm 8 Release S/Ku band antenna 2 from support arm
13	5	**Deployment Status** Bit 1 Release S/Ku band antenna 3 from support arm 2 Release S/Ku band antenna 4 from support arm 3 Release UHF antenna from support arm 4 Spare 5 Spare 6 Spare 7 Spare 8 Spare
	6	**Power Status** Bit 1 Voltage limiter 1 ON 2 Voltage limiter 2 ON 3 Spare 4 Spare 5 Spare 6 Spare 7 Spare 8 Spare

Table 24 (continued)

Main Frame Word	Subcommutation Channel	
13	7	Communication Status
		Bit
		1 Frequency synthesizer A ON
		2 Frequency synthesizer B ON
		3 Frequency synthesizer status
		4 Frequency synthesizer status
		5 Frequency synthesizer status
		6 Frequency synthesizer status
		7 Frequency synthesizer status
		8 Frequency synthesizer status
15		Status Word 15
		Bit
		1 Spare
		2 Spare
		3 Spare
		4 Spare
		5 Spare
		6 Spare
		7 Spare
		8 Spare
	Analog Subcommutators – Despun	
17	0	UHF power amplifier 7 temperature
	1	UHF power amplifier 8 temperature
	2	UHF power amplifier 9 temperature
	3	UHF power amplifier 10 temperature
	4	S band power amplifier 1 temperature
	5	S band power amplifier 2 temperature
	6	S band power amplifier 3 temperature
	7	S band power amplifier 4 temperature
19	0	Forward shelf temperature 1
	1	Forward shelf temperature 2
	2	Aft shelf temperature 1
	3	Aft shelf temperature 2
	4	Auxiliary battery voltage
	5	Ku band transmitter A temperature
	6	Ku band transmitter B temperature
	7	Heater bank A current

Table 24 (concluded)

Main Frame Word	Subcommutation Channel	
21	0	Heater bank B current
	1	Heater bank C current
	2	Heater bank D current
	3	Spare
	4	Spare
	5	Spare
	6	Spare
	7	Spare
	8	Spare
23	0	BAPTA hub temperature 1
	1	BAPTA hub temperature 2
	2	UHF power amplifier 1 temperature
	3	UHF power amplifier 2 temperature
	4	UHF power amplifier 3 temperature
	5	UHF power amplifier 4 temperature
	6	UHF power amplifier 5 temperature
	7	UHF power amplifier 6 temperature

TABLE 25. COMMAND ASSIGNMENTS

Summary	Despun	Spinning
Communications	165	0
Deployment mechanisms	40	0
Antenna operations	16	0
TT&C	3	11
Power	3	27
Controls	0	26
RCS	0	33
Subtotal	227	97
Spares	28	30
Total	255	127

Communications

Despun

1) Frequency synthesizer A ON, B OFF
2) Frequency synthesizer B ON, A OFF
3) Frequency synthesizer both OFF
4) Master oscillator select A
5) Master oscillator select B
6) Frequency synthesizer A frequency step for S band transmit local oscillator 1
7) Frequency synthesizer B frequency step for S band transmit local oscillator 1
8) Frequency synthesizer A frequency step for S band receive local oscillator 1
9) Frequency synthesizer B frequency step for S band receive local oscillator 1
10) Frequency synthesizer A frequency step for S band transmit local oscillator 2
11) Frequency synthesizer B frequency step for S band transmit local oscillator 2
12) Frequency synthesizer A frequency step for S band receive local oscillator 2
13) Frequency synthesizer B frequency step for S band receive local oscillator 2
14) Frequency synthesizer A frequency step for S band transmit local oscillator 3
15) Frequency synthesizer B frequency step for S band transmit local oscillator 3
16) Frequency synthesizer A frequency step for S band receive local oscillator 3
17) Frequency synthesizer B frequency step for S band receive local oscillator 3
18) Ku band receiver command/LDR forward, A ON, B OFF
19) Ku band receiver command/LDR forward, B ON, A OFF
20) Ku band receiver command/LDR forward, both OFF

Table 25 (continued)

Despun

21)	Ku band receiver MDR/HDR forward, A ON, B OFF
22)	Ku band receiver MDR/HDR forward, B ON, A OFF
23)	Ku band receiver MDR/HDR forward, both OFF
24)	Antenna tracking modulator driver select A (MDR/HDR forward)
25)	Antenna tracking modulator driver select B (MDR/HDR forward)
26)	Ku band receiver HDR return 1, A ON, B OFF
27)	Ku band receiver HDR return 1, B ON, A OFF
28)	Ku band receiver HDR return 1, both OFF
29)	Antenna tracking modulator driver select A (HDR return 1)
30)	Antenna tracking modulator driver select B (HDR return 1)
31)	Ku band receiver HDR return 2, A ON, B OFF
32)	Ku band receiver HDR return 2, B ON, A OFF
33)	Ku band receiver HDR return 2, both OFF
34)	Antenna tracking modulator driver select A (HDR return 2)
35)	Antenna tracking modulator driver select B (HDR return 2)
36)	Ku band receiver HDR return 1 bandwidth select: 100 MHz
37)	Ku band receiver HDR return 1 bandwidth select: 50 MHz
38)	Ku band receiver HDR return 1 bandwidth select: 10 MHz
39)	Ku band receiver HDR return 2 bandwidth select: 100 MHz
40)	Ku band receiver HDR return 2 bandwidth select: 50 MHz
41)	Ku band receiver HDR return 2 bandwidth select: 10 MHz
42)	Ku band transmitter HDR return 1, A ON, B OFF
43)	Ku band transmitter HDR return 1, B ON, A OFF
44)	Ku band transmitter HDR return 1, both OFF
45)	Ku band transmitter HDR return 1, select TWT A
46)	Ku band transmitter HDR return 1, select TWT B
47)	Ku band transmitter HDR return 2, A ON, B OFF
48)	Ku band transmitter HDR return 2, B ON, A OFF
49)	Ku band transmitter HDR return 2, both OFF
50)	Ku band transmitter HDR return 2, select TWT A
51)	Ku band transmitter HDR return 2, select TWT B
52)	Ku band transmitter MDR/LDR, A ON, B OFF
53)	Ku band transmitter MDR/LDR, B ON, A OFF
54)	Ku band transmitter MDR/LDR, both OFF
55)	Ku band transmitter MDR/LDR, select TWT A

Table 25 (continued)

Despun	
56)	Ku band transmitter MDR/LDR, select TWT B
57)	Ku band transmitter HDR forward 1, A ON, B OFF
58)	Ku band transmitter HDR forward 1, B ON, A OFF
59)	Ku band transmitter HDR forward 1, both OFF
60)	Ku band transmitter HDR forward 1, select TWT A
61)	Ku band transmitter HDR forward 1, select TWT B
62)	Ku band transmitter HDR forward 2, A ON, B OFF
63)	Ku band transmitter HDR forward 2, B ON, A OFF
64)	Ku band transmitter HDR forward 2, both OFF
65)	Ku band transmitter HDR forward 2, select TWT A
66)	Ku band transmitter HDR forward 2, select TWT B
67)	UHF transmitter driver, A ON, B OFF
68)	UHF transmitter driver, B ON, A OFF
69)	UHF transmitter driver, both OFF
70)	UHF power amplifier 1 ON
71)	UHF power amplifier 1 OFF
72)	UHF power amplifier 2 ON
73)	UHF power amplifier 2 OFF
74)	UHF power amplifier 3 ON
75)	UHF power amplifier 3 OFF
76)	UHF power amplifier 4 ON
77)	UHF power amplifier 4 OFF
78)	UHF power amplifier 5 ON
79)	UHF power amplifier 5 OFF
80)	UHF power amplifier 6 ON
81)	UHF power amplifier 6 OFF
82)	UHF power amplifier 7 ON
83)	UHF power amplifier 7 OFF
84)	UHF power amplifier 8 ON
85)	UHF power amplifier 8 OFF
86)	UHF power amplifier 9 ON
87)	UHF power amplifier 9 OFF
88)	UHF power amplifier 10 ON
89)	UHF power amplifier 10 OFF
90)	VHF horizontal receiver 1, A ON, B OFF

Table 25 (continued)

Despun	
91)	VHF horizontal receiver 1, B ON, A OFF
92)	VHF horizontal receiver 2, A ON, B OFF
93)	VHF horizontal receiver 3, A ON, B OFF
94)	VHF horizontal receiver 3, A ON, B OFF
95)	VHF horizontal receiver 3, B ON, A OFF
96)	VHF horizontal receiver 4, A ON, B OFF
97)	VHF horizontal receiver 4, B ON, A OFF
98)	VHF horizontal receiver 5, A ON, B OFF
99)	VHF horizontal receiver 5, B ON, A OFF
100)	VHF horizontal receiver, all OFF
101)	VHF vertical receiver 1, A ON, B OFF
102)	VHF vertical receiver 1, B ON, A OFF
103)	VHF vertical receiver 2, A ON, B OFF
104)	VHF vertical receiver 2, B ON, A OFF
105)	VHF vertical receiver 3, A ON, B OFF
106)	VHF vertical receiver 3, B ON, A OFF
107)	VHF vertical receiver 4, A ON, B OFF
108)	VHF vertical receiver 4, B ON, A OFF
109)	VHF vertical receiver 5, A ON, B OFF
110)	VHF vertical receiver 5, B ON, A OFF
111)	VHF vertical receivers, all OFF
112)	VHF receivers select upconverter A
113)	VHF receivers select upconverter B
114)	VHF receivers select frequency source A
115)	VHF receivers select frequency source B
116)	Order wire receiver, A ON, B OFF
117)	Order wire receiver, B ON, A OFF
118)	Order wire receiver, both OFF
119)	S band transponder, A ON, B OFF
120)	S band transponder, B ON, A OFF
121)	S band transponder, both OFF
122)	S band transmitter 1, A ON, B OFF
123)	S band transmitter 1, B ON, A OFF
124)	S band transmitter 1, both OFF
125)	S band transmitter 2, A ON, B OFF

Table 25 (continued)

Despun	
126)	S band transmitter 2, B ON, A OFF
127)	S band transmitter 2, both OFF
128)	S band transmitter 3, A ON, B OFF
129)	S band transmitter 3, B ON, A OFF
130)	S band transmitter 3, both OFF
131)	S band transmitter 1 high level select
132)	S band transmitter 1 low level select
133)	S band transmitter 2 high level select
134)	S band transmitter 2 low level select
135)	S band transmitter 3 high level select
136)	S band transmitter 3 low level select
137)	S band receiver 1, A ON, B OFF
138)	S band receiver 1, B ON, A OFF
139)	S band receiver 1, both OFF
140)	S band receiver 2, A ON, B OFF
141)	S band receiver 2, B ON, A OFF
142)	S band receiver 2, both OFF
143)	S band receiver 3, A ON, B OFF
144)	S band receiver 3, B ON, A OFF
145)	S band receiver 3, both OFF
146)	S band MDR receiver 1 step attenuator IN
147)	S band MDR receiver 1 step attenuator OUT
148)	S band MDR receiver 2 step attenuator IN
149)	S band MDR receiver 2 step attenuator OUT
150)	S band MDR receiver 3 step attenuator IN
151)	S band MDR receiver 3 step attenuator OUT
152)	HDR/MDR/LDR antenna to A
153)	HDR/MDR/LDR antenna to B
154)	HDR/MDR/LDR antenna to C
155)	HDR/MDR/LDR antenna to D
156)	HDR S/Ku band antenna 3 to A
157)	HDR S/Ku band antenna 3 to B
158)	HDR S/Ku band antenna 3 to C
159)	HDR S/Ku band antenna 3 to D
160)	HDR S/Ku band antenna 4 to A

Table 25 (continued)

Despun	
161)	HDR S/Ku band antenna 4 to B
162)	HDR S/Ku band antenna 4 to C
163)	HDP S/Ku band antenna 4 to D
164)	Ku band receiver HDR return 1, bandwidth select: 200 MHz
165)	Ku band receiver HDR return 2, bandwidth select: 200 MHz
	Deployment Mechanisms
Despun	
1)	Release support arm Ku band antenna 1
2)	Release support arm S/Ku band antenna 2
3)	Release center support S/Ku band antenna 3/4
4)	Release S/Ku band antenna 3 arm
5)	Release S/Ku band antenna 4 arm
6)	Release UHF antenna arm
7)	Release Astromast stowage lock
8)	Extend Astromast
9)	Release VHF antenna element 1 - 4 arms
10)	Release VHF antenna element 5 arm
11)	Release VHF element 1 from support arm
12)	Release VHF element 2 from support arm
13)	Release VHF element 3 from support arm
14)	Release VHF element 4 from support arm
15)	Release VHF element 5 from support arm
16)	Sever cable on VHF element 1
17)	Sever cable on VHF element 2
18)	Sever cable on VHF element 3
19)	Sever cable on VHF element 4
20)	Sever cable on VHF element 5
21)	Unfurl by mechanical drive VHF element 1
22)	Unfurl by mechanical drive VHF element 2
23)	Unfurl by mechanical drive VHF element 3
24)	Unfurl by mechanical drive VHF element 4
25)	Unfurl by mechanical drive VHF element 5
26)	Release Ku band antenna 1 from support arm
27)	Release Ku/S band antenna 2 from support arm

Table 25 (continued)

Despun	
28)	Release S/Ku band antenna 3 from support arm
29)	Release S/Ku band antenna 4 from support arm
30)	Release UHF antenna from support arm
31)	Sever cable on Ku band antenna 1
32)	Sever cable on S/Ku band antenna 2
33)	Sever cable on S/Ku band antenna 3
34)	Sever cable on S/Ku band antenna 4
35)	Sever cable on UHF antenna
36)	Unfurl by mechanical drive Ku band antenna 1
37)	Unfurl by mechanical drive S/Ku band antenna 2
38)	Unfurl by mechanical drive S/Ku band antenna 3
39)	Unfurl by mechanical drive S/Ku band antenna 4
40)	Unfurl by mechanical drive UHF antenna
	Antenna Operations
Despun	
1)	Step Ku band antenna 1 azimuth east
2)	Step S/Ku band antenna 2 azimuth east
3)	Step S/Ku band antenna 3 azimuth east
4)	Step S/Ku band antenna 4 azimuth east
5)	Step Ku band antenna 1 azimuth west
6)	Step S/Ku band antenna 2 azimuth west
7)	Step S/Ku band antenna 3 azimuth west
8)	Step S/Ku band antenna 4 azimuth west
9)	Step Ku band antenna 1 elevation south
10)	Step S/Ku band antenna 2 elevation south
11)	Step S/Ku band antenna 3 elevation south
12)	Step S/Ku band antenna 4 elevation south
13)	Step Ku band antenna 1 elevation north
14)	Step S/Ku band antenna 2 elevation north
15)	Step S/Ku band antenna 3 elevation north
16)	Step S/Ku band antenna 4 elevation north

Table 25 (continued)

Telemetry, Tracking, and Command

Despun

1) Telemetry encoder A ON
2) Telemetry encoder B ON
3) Telemetry encoders, both OFF

Power Subsystem

Despun

1) Voltage limiter 1 ON
2) Voltage limiter 2 ON
3) Voltage limiters, both OFF

Telemetry, Tracking, and Command

Spinning

1) Telemetry encoder 1 PCM mode
2) Telemetry encoder 2 PCM mode
3) Telemetry encoder 1 ON
4) Telemetry encoder 1 OFF
5) Telemetry encoder 2 ON
6) Telemetry encoder 2 OFF
7) Telemetry encoder 1 FM mode
8) Telemetry encoder 2 FM mode
9) Telemetry transmitter, A ON, B OFF
10) Telemetry transmitter, B ON, A OFF
11) Telemetry transmitters, both OFF

Power Subsystem

Spinning

1) Battery 1 charge ON
2) Battery 2 charge ON
3) Battery 3 charge ON
4) Battery 4 charge ON
5) Battery charge OFF
6) Trickle charge ON
7) Trickle charge battery 1 OFF

Table 25 (continued)

Power Subsystem (cont)

Spinning

8) Trickel charge battery 2 OFF
9) Trickle charge battery 3 OFF
10) Trickel charge battery 4 OFF
11) Reconditioning discharge battery 1 ON
12) Reconditioning discharge battery 2 ON
13) Reconditioning discharge battery 3 ON
14) Reconditioning discharge battery 4 ON
15) Reconditioning discharge batteries OFF
16) Set charge temperature limit 1
17) Set charge temperature limit 2
18) Set charge temperature limit 3
19) Set charge temperature limit 4
20) Thermal charge limit set override
21) Voltage limiters OFF
22) Voltage limiter 1 ON
23) Voltage limiter 2 ON
24) Voltage limiter 3 ON
25) Voltage limiter 4 ON
26) Voltage limiter 5 ON
27) Voltage limiter 6 ON

Controls

Spinning

1) Earth sensors ON
2) Earth sensor 1 OFF
3) Earth sensor 2 OFF
4) Earth sensor 3 OFF
5) Select earth sensor 1
6) Select earth sensor 2
7) Select earth sensor 3
8) Motor drivers ON
9) Motor driver 1 OFF
10) Motor driver 2 OFF
11) Rate command latch 1

Table 25 (continued)

	Controls (cont)
Spinning	
12)	Rate command latch 2
13)	Despin control electronics 1 and 2 OFF
14)	Despin control electronics 1 ON
15)	Despin control electronics 2 ON
16)	Interlock enable
17)	Interlock disable
18)	Command limiter ON
19)	Command limiter OFF
20)	Motor driver 1 low gain
21)	Motor driver 1 high gain
22)	Motor driver 2 low gain
23)	Motor driver 2 high gain
24)	Active nutation control 1 ON
25)	Active nutation control 2 ON
26)	Active nutation control OFF
	Reaction Control Subsystem and Apogee Motor
Spinning	
1)	Axial jet 1
2)	Axial jet 2
3)	Axial jets 1 and 2
4)	Radial jet 1
5)	Radial jet 2
6)	Latching valve 1 OPEN
7)	Latching valve 1 CLOSE
8)	Latching valve 2 OPEN
9)	Latching valve 2 CLOSE
10)	Latching valve 3 OPEN
11)	Latching valve 3 CLOSE
12)	Latching valve 4 OPEN
13)	Latching valve 4 CLOSE
14)	Latching valve 5 OPEN
15)	Latching valve 5 CLOSE

Table 25 (continued)

Reaction Control Subsystem and Apogee Motor (cont)

Spinning

16)	Apogee motor squib 1 (decoder 1)
17)	Apogee motor squib 2 (decoder 2)
18)	Apogee motor heaters ON
19)	Apogee motor heater 1 OFF
20)	Apogee motor heater 2 OFF
21)	Apogee motor heater 3 OFF
22)	Apogee motor heater 4 OFF
23)	Spinup valve heaters OFF
24)	Spinup valve heaters ON
25)	Radial valve heater OFF
26)	Radial valve heater ON
27)	Axial valve heater ON
28)	Axial valve heater OFF
29)	Spinup thrusters 1
30)	Spinup thrusters 2
31)	SCL enable
32)	SCL disable
33)	SCL execute

4.3.3 Antennas

The antenna subsystem on the Space Shuttle launched TDRS spacecraft consists of 11 antennas that provide the HDR, MDR and LDR telecommunication service as well as the satellite command links. The antennas are supported off the forward and aft despun platform in orbital flight configuration arrangement as illustrated in Figure 51. All antennas are tied at two ends to the spacecraft despun platforms during launch, ejection from the Space Shuttle, and during the apogee motor burn when the spacecraft spin assembly is rotating. The antenna on-orbit deployment sequence is illustrated in Figures 52 and 53. Initially the five-element AGIPA system is deployed by activating the squib of the Astromast tiedown lock and rotating the mast stowage cannister 180 degrees. The mast positioned normal to the aft despun spacecraft platform is extended with a motor drive mechanism by ground command. The five antenna elements remain locked to a central support arm during the mast extension. Next, five radial support arms are sequentially positioned with spring loaded hinges and the individual VHF backfire reflectors are pointed normal to the spacecraft axis by spring drives. Finally, the AGIPA antenna reflectors are unfurled by motor drive mechanisms. The deployment steps of the forward antenna assembly are as follows:

1) Release sequentially the support arm locks of the S/Ku and Ku band antennas and rotate them by spring motor drive into the proper position.

2) Unlock individually the stowed reflector units from their support arms and position them normal to the support links by activating the two axis gimbal drive mechanisms.

3) Erect and deploy the UHF backfire antenna by releasing its tiedown lock from the central forward mast.

4) Unfurl the four rib mesh reflectors with their motor drive mechanism.

The antennas are dimensioned for sufficient strength to withstand 30 g quasi-static acceleration loading and for minimum structural stiffness of 50 and 4 Hz when stowed or deployed, respectively. Mechanical and RF antenna design characteristics are described in the following sections.

4.3.3.1 AGIPA

An adaptive ground implemented phased array (AGIPA) has been implemented for the LDR return link from user spacecraft.

The AGIPA consists of five backfire antenna elements which when deployed are equally spaced on an 8.5 meter circle. The stowage concept of these VHF elements is essentially that of the S/Ku band rib mesh reflector described in subsection 4.3.3.2. The considerably lesser reflector

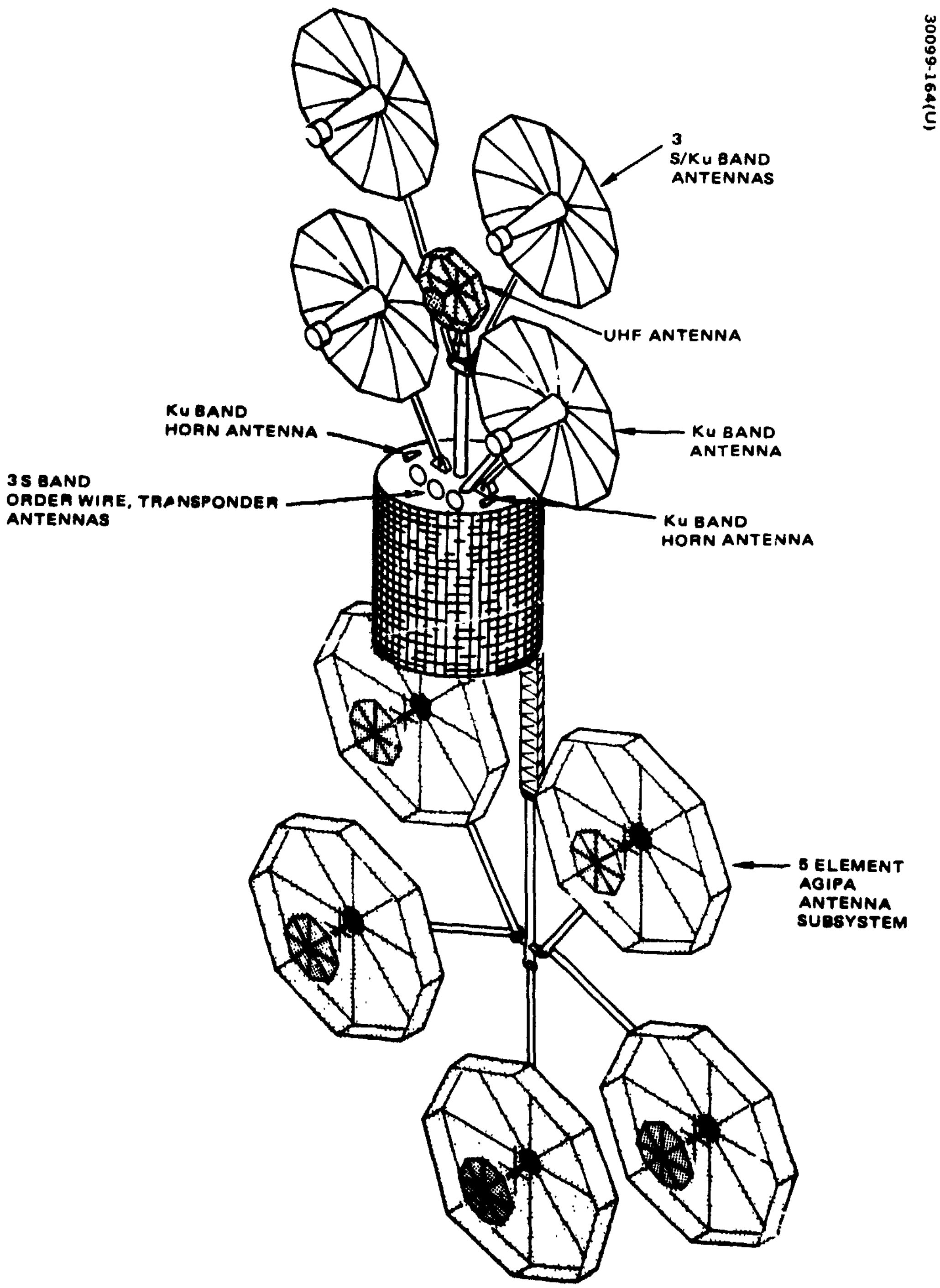


Figure 51. TDR Spacecraft Orbital Configuration

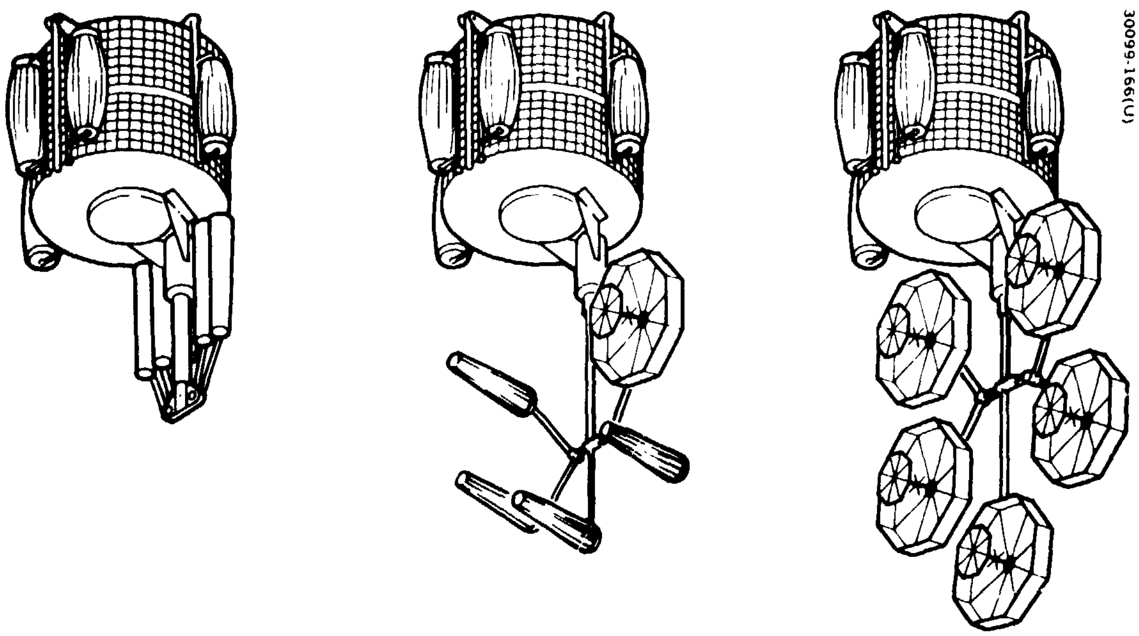


Figure 52. AGIPA Antenna Assembly Deployment

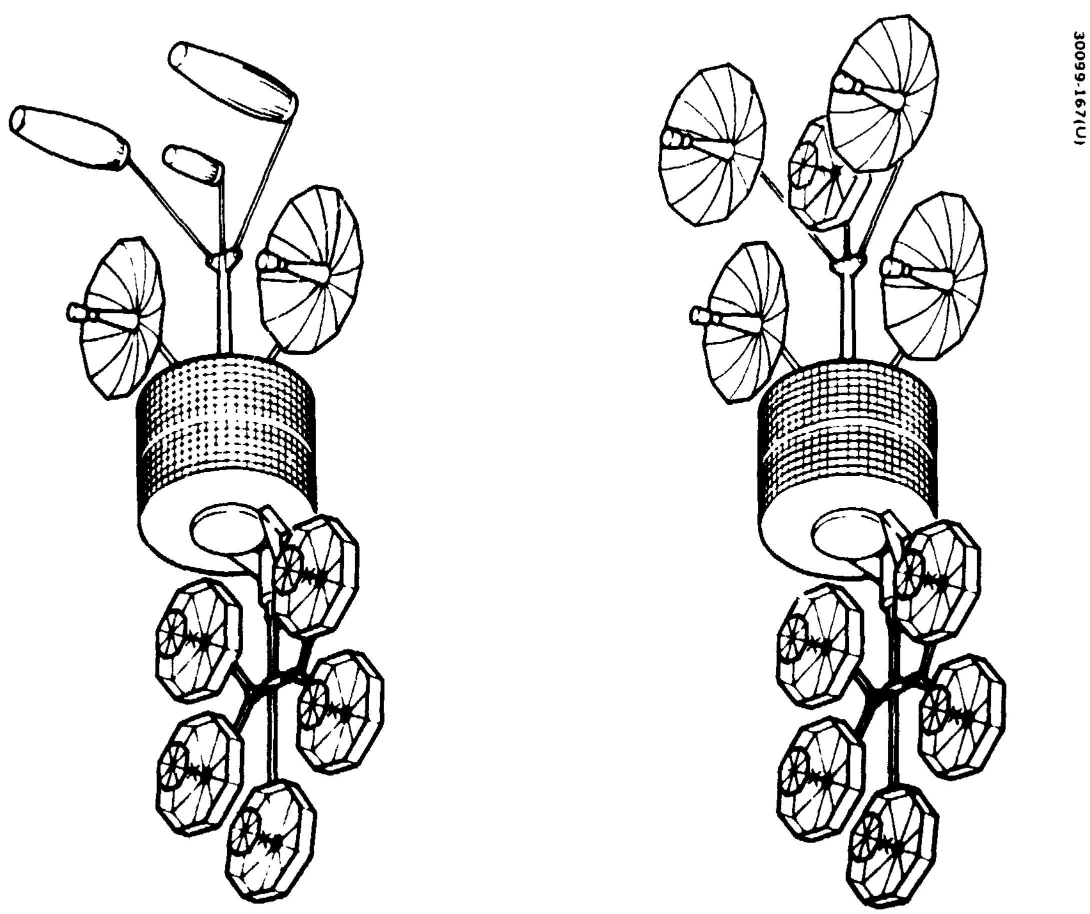


Figure 53. Forward Antenna Assembly Deployment

precision requirement at VHF frequency, however, allows use of flex joints at the rib roots for a simple deployment mechanization. The primary reflective surface of 4.40 meter diameter employs a 1.25 cm grid mesh and 8 inch aluminum tubular ribs. A central tube supports the crossed dipole feed and a reflective cavity plate (mesh) at $\lambda/4$ and $\lambda/2$ spacing from the primary reflector.

The AGIPA system is nested around the antenna support mast in the spacecraft launch configuration. In order, a deployable lattice truss boom (Astromast-SPAR Aerospace Company) positions the antenna system aft of the spacecraft for balanced solar pressure torque.

Each of the five AGIPA elements employs two coaxial cable feed lines of 1.25 cm Alumnispline which are routed along the structural supports. Dual linear polarization is used. The performance characteristics for the reflector elements are listed in Table 26.

4.3.3.2 S/Ku and Ku Band Deployment Antennas

Three dual frequency S/Ku band deployable antenna reflectors and a single frequency Ku band antenna are utilized on the Space Shuttle launched launched satellite configuration.

The S and Ku band dual frequency antenna selected for the TDRS are deployable rib mesh reflectors of 3.82 meter diameter. The primary surface contour is shaped by 12 aluminum ribs of 3.8 cm diameter and tapered wall thicknesses from 0.015 to 0.03 cm. The reflector contour precision to within 0.025 cm rms is accomplished by the use of a secondary back mesh and adjustable tension ties between front and back mesh.

A central cone supports the S band feed assembly and the Ku band subreflector (Cassegrainian concept-dicroic support structure). The antenna

TABLE 26. VHF – SHORT BACKFIRE ELEMENT PERFORMANCE

Frequency band	136 to 138 MHz
Aperture diameter	4.35 meters
Aperture gain*	15.0 dB
Reflector surface loss	0.01 dB
Reflector mesh I^2R	0.02 dB
Coaxial cable loss	0.03 dB
VSWR loss (1:3:1)	0.08 dB
Total loss	0.14 dB
Antenna peak gain	14.7 dB
Antenna field of view gain	12.7 dB (±13°)
Polarization sense	Linear: horizontal and vertical

*L.R. Dog, Backfire Yagi Antenna Measurements.

hub measures 45 cm in diameter and houses the mechanical deployment drive and linkage mechanism. Redundant torque spring and motor drives unfurl the reflector in orbit and in 1 g environment. This rib-dominated mesh antenna system was designed by Radiation, Inc. Its mechanical and RF performance characteristics have been demonstrated in a NASA-funded program. The mass estimated by Radiation, Inc. for the 3.8 meter S/Ku band deployable antenna is 8.9 kg. Figure 54 shows the antenna in its stowed configuration.

The reflective mesh is constructed from five-strand bundles of 0.0018 cm Chromel-R wire knitted into a wire screen. A coarse mesh is used as a secondary drawing surface for contouring the front mesh while minimizing the antenna mass. The mesh is attached to the ribs in a tensioned state.

Deployment of the reflector from the stowed to the fully open position is precisely controlled to prevent impact loading of the rib structures and mesh, thereby assuring that 1) the preset parabolic surface is not distorted by the deployment action, and 2) no mesh loading conditions result that exceed the mesh strength limits. The deployment mechanism shown in Figure 55 utilizes redundant energy drive systems to rotate a ball screw within a recirculating ball nut. The resultant linear motion of the ball nut serves to rotate each rib from the stowed to deployed position through individual linkages to each rib. The primary drive of this system is a constant torque spring motor. This spring motor provides sufficient energy to deploy the antenna in any orientation under gravity conditions. In a zero gravity condition, the spring motor capability exceeds the deployment energy requirements. A backup drive system of two miniature torque motor functions then as dynamic brakes, controlling the deployment and requiring no electrical power. If required to deliver power, the motors can increase the torque to the ball-screw by as much as a factor of four. Latching in the deployed condition is accomplished by driving the ball nut carrier and linkages through an overcenter condition (relative to the pivot arms).

The RF performance parameters for the S and Ku band antennas are summarized in Table 27. For the ground link only Ku band operation is required. Without the interference created by use of a second frequency, the antenna exhibits slightly improved RF characteristics (+0.2 dB) and is somewhat lighter (0.7 kg).

4.3.3.3 Short Backfire Broadbeam Antennas

The short backfire type antenna has been adapted for the broad beam antenna requirements because of its compact size, minimum mass, and complexity. Test data show that this antenna type can develop an aperture efficiency of 75 percent for reasonably narrow bandwidths. This antenna configuration is used for the VHF AGIPA. UHF forward link, the S band transponder, and for the order wire service at S band.

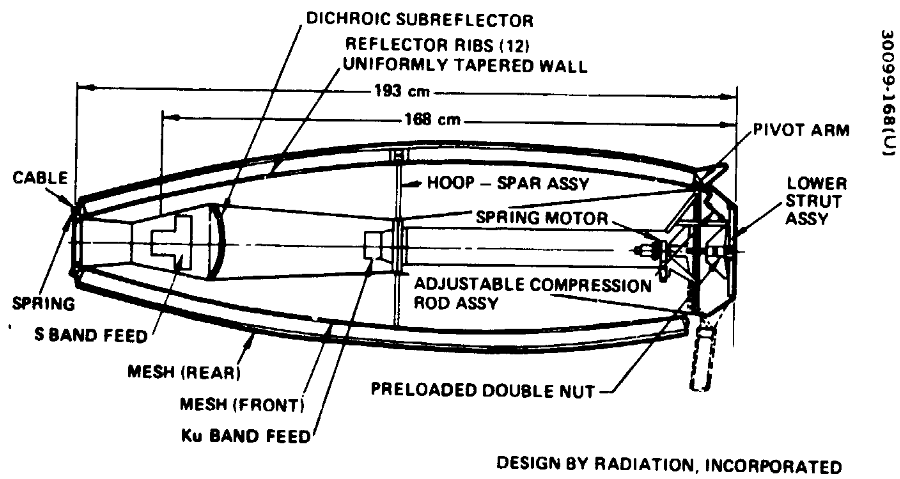


Figure 54. S/Ku Band Deployable Antenna Structural Design

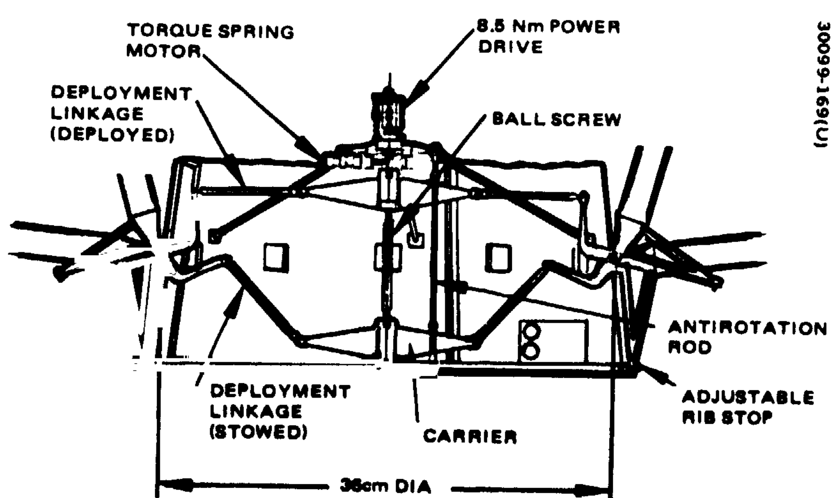


Figure 55. Antenna Mechanical Deployment Drive

TABLE 27. S/Ku BAND HIGH GAIN ANTENNA

Frequency Band	S Band		Ku Band	
Frequency, GHz	2.07	2.25	13.7	14.9
Aperture diameter, meters	3.82		3.82	
Aperture area gain, dB	38.4	39.1	54.7	55.6
Spillover and amplitude taper loss, dB	1.35	1.35	0.86	0.86
Phase loss, dB	0.14	0.14	0.04	0.04
Blockage loss, dB	0.19	0.20	0.08	0.08
Crosspolarization loss, dB	0.19	0.20	0.32	0.32
Radome loss, dB	0.19	0.10	0.16	0.16
Dichroic subreflector loss, dB	0.20	0.20	0.20	0.20
Surface tolerance loss, dB	0.02	0.02	0.32	0.36
Mesh I^2R loss	0.05	0.05	0.15	0.15
Hybrid loss, dB	0.20	0.20	N.A.	N.A.
Transmission line loss, dB	0.35	0.35	0.04	0.04
Feed and polarizer I^2R loss, dB	N.A.	N.A.	0.32	0.32
Comparator loss, dB	N.A.	N.A.	0.20	0.20
VSWR loss, dB	0.12	0.12	0.08	0.08
Total losses, dB	2.90	2.93	2.77	2.81
Total efficiency, percent	51.3	51.0	53.0	52.5
Antenna peak gain, dB	35.5	36.2	51.9	52.8
Half power beamwidth, degrees	2.5	2.3	0.37	0.34
Polarization sense	Circular	Circular (orthogonal)	Circular	Circular

The VHF short backfire design has been described previously. The UHF forward link antenna is 148 cm in diameter and about 37.5 cm high. The RF performance data as determined by analysis for an operational frequency of 401 MHz are listed in Table 28.

The S band order wire antenna is electrically identical to the UHF antenna, except it is scaled to S band. The reflector is made from perforated sheet metal for low cost and light weight. Single sense circular polarization is generated by slot-fed crossed dipoles. The antenna performance parameters are listed in Table 29. The two S band transponder antennas are essentially identical in design and performance to the order wire antenna.

4.3.3.4 Ku Band Horn Antennas

Two Ku band receive horn antennas provide coverage of the northern hemisphere, both have a circular polarization and a beamwidth of 9 degrees by 18 degrees. An array of two fin-loaded pyramidal horn antennas satisfies the CP beam coverage requirements over the 13.4 to 14.2 GHz transmit

TABLE 28. UHF ANTENNA PERFORMANCE

Frequency band	400.5 to 401.5 MHz
Aperture diameter	1.3 meters
Aperture gain	15.0 dB
Reflector surface loss	0.02 dB
Reflector mesh I^2R loss	0.08 dB
Hybrid loss	(0.635 cm) rms
	0.16 dB
Coaxial cable loss	0.09 dB
VSWR loss (1.3:1)	0.08 dB
Total loss	0.48 dB
Antenna peak gain	14.57 dB
Antenna FOV gain	12.50 dB (±13°)
Polarization sense	Circular polarization

TABLE 29. S BAND ORDER WIRE ANTENNA PERFORMANCE

Frequency band		2200 to 2290 MHz
Aperture diameter		26.7 cm
Aperture gain		15.0 dB
Reflector surface loss	0.01 dB	
Reflector I^2R loss	0.01 dB	
Hybrid loss	0.16 dB	
Coaxial cable loss	0.01 dB	
VSWR loss (2.0:1)	0.50 dB	
Total losses		0.69 dB
Antenna peak gain		14.3 dB
Antenna field of view gain (±15 degrees)		11.4 dB
Polarization sense		Circular

frequency. A four-iris square guide polarizer and an orthomode tee are used. For simplicity, the unused orthogonal arm of the orthomode tee has been shorted out. The RF performance characteristics for the Ku band receive horns are summarized in Table 30.

4.3.3.5 Antenna Tracking Mechanisms

Two-axis (elevation and azimuth) tracking mechanisms are employed for all S/Ku and Ku band reflectors for pointing over a range of ±16 degrees. Identical motor drive assemblies are jointed by a gimbal structure resulting in an elevation over azimuth configuration. The gimbal assembly is supported in each axis by the preloaded angular contact ball bearings of the mo motor drive assembly and by an outboard radial deep groove bearning. Dry

TABLE 30. Ku BAND HORN ANTENNA PERFORMANCE

Frequency		13.7 GHz
Aperture area gain ($4\pi A/\lambda^2$)		25.1 dB
Amplitude taper and phase losses	1.93 dB	
Horn I^2R loss	0.03 dB	
Polarizer and transition I^2R loss	0.30 dB	
Waveguide loss (30.4 cm)	0.25 dB	
VSWR loss (1.3:1)	0.08 dB	
Total losses		2.59 dB
Antenna peak gain		22.5 dB
Antenna northern hemisphere gain (±4.5° N-S, ±0.1° E-W)		18.5 dB
Polarization sense		Circular

film lubrication is used throughout the mechanisms for temperature range compatibility and to avoid the need for sealing the moving elements. The S band transmission employs coaxial rotary joints for low RF loss (total of 0.2 dB). At Ku band rotary waveguides are used for RF power transmission across the drive mechanism axis.

The drive mechanism is powered by a permanent magnet, bifilar-wound, phase switched stepper motor producing 200 steps per revolution (1.8 degrees per step). The motor provides ample torque at stepping rates beyond the maximum required for this application and provides positive magnetic holding torque when power is removed. The transmission selected is a high ratio harmonic drive with a reduction of 144:1 resulting in a nominal gimbal movement of 0.0125 degree for each pulse to the stepper motor.

4.3.4 Attitude Control

The attitude control system establishes the spacecraft attitude, provides a stable platform for antenna positioning, and monitors the orientation of the vehicle spin vector and despun platform azimuth for precision antenna pointing. The TDR Gyrostat spacecraft configuration develops gyroscopic rigidity from its spinning rotor, and attitude stability is achieved by passive energy dissipation from the despin nutation damper and by active nutation damping through the despin control system.

The functional criteria and design requirements for the spin axis attitude control are:

1) Attitude control subsystem must provide vehicle asymptotic nutational stability, with residual nutation consistent with antenna pointing accuracy requirements.

2) Nutation transients that occur in normal operation must be rapidly damped.

3) Vehicle must be autonomously stable in failure modes involving large nutation angles.

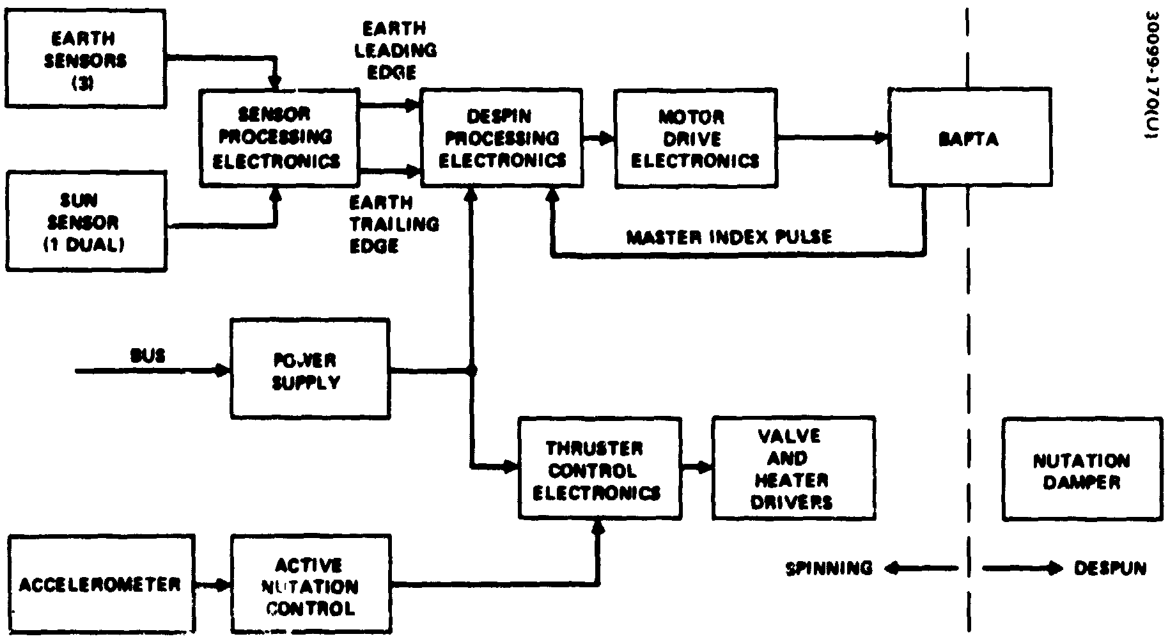


Figure 56. Attitude Control Subsystem Block Diagram

4) Spin axis control requirements are north-south error allocation 0.10 degree, orientation determination 0.20 degree, and system nutation damping time constant 300 seconds.

Table 31 lists the characteristics of the attitude control subsystem.

Figure 56 is a functional block diagram of the attitude control subsystem. Determination and control of the spin axis attitude is accomplished by using rotor mounted sun and earth sensors. The sun sensor provides pulse pairs for measurement of the angle between the sun line of sight and the spacecraft spin axis, while the earth sensors provide earth chordwidth information for attitude measurements. Corrections to attitude are made using commanded pulsing of the jets.

Sensor information for attitude determination is processed by the Hughes ATDET or a similar computer program. This program models disturbance torques, sensor biases, and attitude commands and produces a least squares fit of attitude to the data. The processing algorithm used permits on-orbit calibration of the sensors and updating of solar torque estimates. During transfer orbit, attitude may be determined by 0.2 degree (3 sigma) accuracy, on-orbit accuracy of 0.03 degree (3 sigma) after calibration of sensor biases is achieved.

The TDRS attitude stabilization design incorporates despin control damping of nutation along with using the passive, platform mounted, eddy current nutation damper.

In addition to the techniques for stabilizing the nutation by action of internal elements, an active backup nutation control (ANC) loop using reaction jets has been incorporated to stabilize nutation in a failure mode or to reduce transient nutation during the apogee motor firing and antenna deployment phases of the mission. The method of actively controlling nutation is the following:

1) An accelerometer detects the presence of nutation and establishes the phase and amplitude of the motion with respect to a rotor-fixed coordinate system

TABLE 31. ATTITUDE CONTROL SUBSYSTEM CHARACTERISTICS

Stabilization technique	
Transfer orbit	Stable spinner
Apogee motor firing	Stable spinner
Operational orbit	Gyrostat
Spin rate	60 rpm
Nutation frequency	0.06 Hz
Nutation	<300 s
Spin axis orientation	Orbit normal ±0.5 deg
Attitude determination accuracy	0.1 deg
Antenna pointing accuracy, open loop	0.3 deg
Antenna pointing accuracy, autotrack	0.1 deg

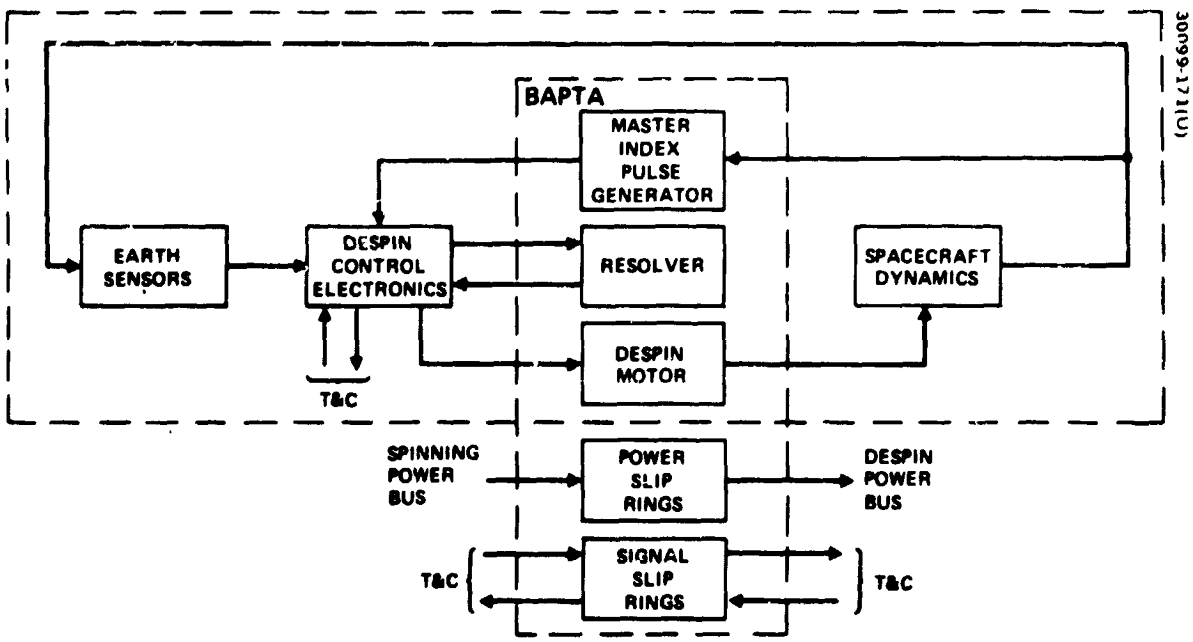


Figure 57. Despin Control Subsystem Block Diagram

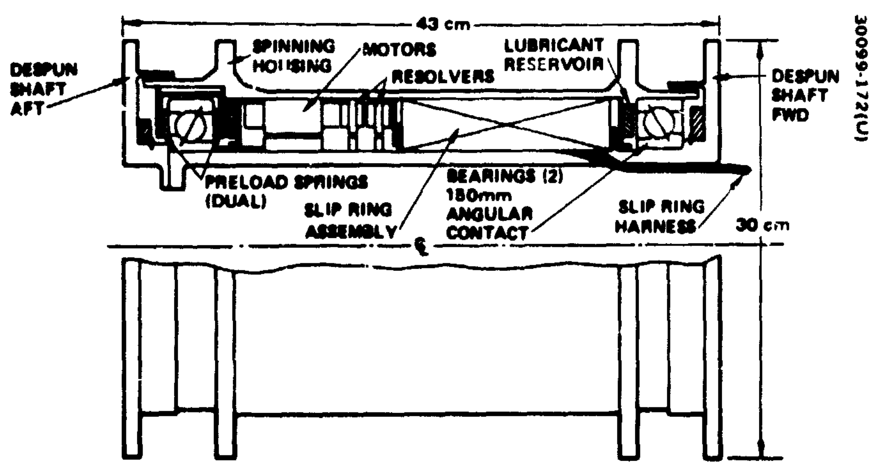


Figure 58. Despin Bearing Assembly

2) The accelerometer output signal is threshold-detected, amplified, and converted to a jet command

3) The axial jet fires once per nutation cycle for a portion of the cycle which results in the application of a transverse torque in opposition to the nutation motion.

Figure 57 is a simplified block diagram of the despin control subsystem (DCS). Three independent earth sensors are mounted on the spinning rotor and are used to supply rotor phase information relative to the earth center to the despin control subsystem. For on-station operation, only a single earth sensor is required for despin control. Use of three elevation orientations allows selection of the sensor to be used by ground command well in advance of sun or moon interference and provides adequate redundancy.

The bearing and power transfer assembly (BAPTA) provides electrical and mechanical interconnection between the spinning and despun sections of the satellite. The BAPTA consists of a bearing assembly, a motor drive assembly, and a slip ring assembly for signal and power transfer between the spun and despun sections of the spacecraft. Figure 58 shows the despin bearing assembly and Table 32 lists the despun bearing characteristics.

The despin control electronics (DCE) processes the inertial rotor phase information from an earth sensor and the relative platform phase information from the MIP (sampled once every rotor spin revolution) and generates continuous control torque commands to the BAPTA torque motor. It contains both rate and tracking loop control logic to ensure automatic despin of the platform and acquisition of the earth. The DCE contains the loss of sensor detection logic to provide platform rate stability in the event of loss of an earth sensor and accepts ground commands for platform rate control and failure mode ground despin control.

TABLE 32. DESPIN BEARING CHARACTERISTICS

Bearing size	150 mm
Estimated mass	35 kb
Friction torque	0.45 N-m
Drive power	10 W
Power slip rings	
Number	4
Brushes/ring	6
Signal slip rings	
Number	12
Brushes/ring	4

There are four basic operating modes for the despin control subsystem:

1) In the normal tracking mode, the despin system aligns the despin antenna boresight to the center of the earth as sensed by the spinning earth sensors. Because of the wide variation in platform inertia due to antenna deployment, a low gain tracking mode has been implemented for initial orbital operation of the despin subsystem. When the DCE is turned on, a lower control loop gain is activated. Once initial orbit is achieved and the antennas are deployed, the higher gain mode is selected by ground command.

2) The rate control mode uses an inner rate loop to ensure automatic despin and acquisition during initial rotor spinup and following apogee boost. A three level ground commandable ± 12 or 24 degrees/second rate bias is included in the DCE for controlling the platform rate. The magnitude of the maximum commandable rate torque is scaled so as to override the tracking loop and generate the desired platform rate.

3) In pseudo-earth mode, the tracking and rate loops operate using ground transmitted leading and trailing edge pulses, which are locked in frequency to the rotor spin rate. The required spin synchronous pulse train is obtained by use of the sun sensor pulses which are available on real time FM telemetry. An additional sun pulse delayed by 14 degrees of spin pulse from the telemetry sun pulse is created. This pulse train is then sent through the normal command channel to the despin control electronics. By controlling the phase of the retransmitted pulses with respect to the original sun pulse, the azimuth orientation of the payload antenna can be controlled.

4) In the event of loss of earth sensor pulses, automatic onboard logic will supply a once per revolution pulse to the rate control logic. The pulse frequency is based on a fixed clock rate (internal to the DCE) set to the nominal spin speed. Therefore, in the event of a sensor loss, a slight platform rate will develop due to deviations in actual spin speed from the nominal. By ground-commanding an alternate sensor, automatic despin and reacquisition will occur.

Determination of the platform orientation is accomplished by means of an earth center-finding technique. The linear range of the error detection is ±7 degrees for north earth and south earth oriented sensors and ±8 degrees for the center earth sensor. For errors beyond the linear range (as in the case when the platform is rotating), the sensed error is held at plus or minus the saturation value by the DCE, by use of an electronically generated delayed MIP, which is 180 degrees away from the actual MIP. This ensures the correct platform direction of rotation during acquisition for shortest acquisition time.

Determination of inertial platform rate is accomplished by measuring the change in platform position over one rotor spin revolution. The rate logic utilizes the earth leading edge and MIP pulses along with a fixed frequency clock, to form, digitally, this first-back-difference of position. At the occurrence of the earth leading edge pulse an upcounter is set to zero and proceeds to then count from the leading pulse to the MIP, using a crystal-controlled oscillator as the basic count clock. At the occurrence of the MIP the number occurring the uncounter is transferred to a downcounter and the downcounter is allowed to count from the text leading edge to MIP. At the occurrence of each MIP, the number contained in the downcounter represents the change in platform position over one sample.

The operation of the tracking loop is illustrated in the block diagram Figure 59. The sample and hold output of the position error detector is used to drive an analog shaping network whose dynamics have been selected to provide stable closed loop pointing control and meet the despin system requirements. The resulting output of the shaping network is a torque command to the BAPTA.

The motor used in the despin control subsystem is a two-phase, 16 pole, ac motor which requires in-phase sine and cosine driving voltages to generate the required rotating magnetic field. To operate as a dc motor, these sine and cosine voltages must be artifically generated. This is accomplished using a resolver in the BAPTA. A precise phase relation is maintained between the motor rotor and resolver by keying them to a common shaft. The resolver is excited by a 4 kHz carrier from the DCE. The sine and cosine resolver outputs are then synchronously demodulated to remove the carrier and amplified to drive the redundant BAPTA motor sine and cosine windings. One sine/cosine pair are driven by the motor driver in a single despin control electronics unit. However, the DCE motor driver inputs are cross-strapped so that each DCE can drive either or both of the motor driver/motor pairs.

When the DCE receives power, it turns on with several of the internal stages in preferred states. The DCE last utilized (ground command selected) is activated in the low gain mode. Both motor drivers are active and the ground mode logic is off. The rate bias is zero and center earth sensor is selected as the despin reference. This initialization logic is in part determined by the system requirement to recover automatically from a flat spin condition due to battery failure upon exit from eclipse.

4.3.5 Reaction Control Subsystem

The RCS must provide capability for 128.7 meters/second change in velocity. The ΔV budget shown in Table 33 indicates the maneuver requirements. It shows that injection trim and station change dominate all other maneuvers.

The RCS is a blowdown type monopropellant hydrazine system. Catalytic decomposition of hydrazine produces hot gas, developing impulse for all required velocity, attitude, and spin speed control maneuvers, except

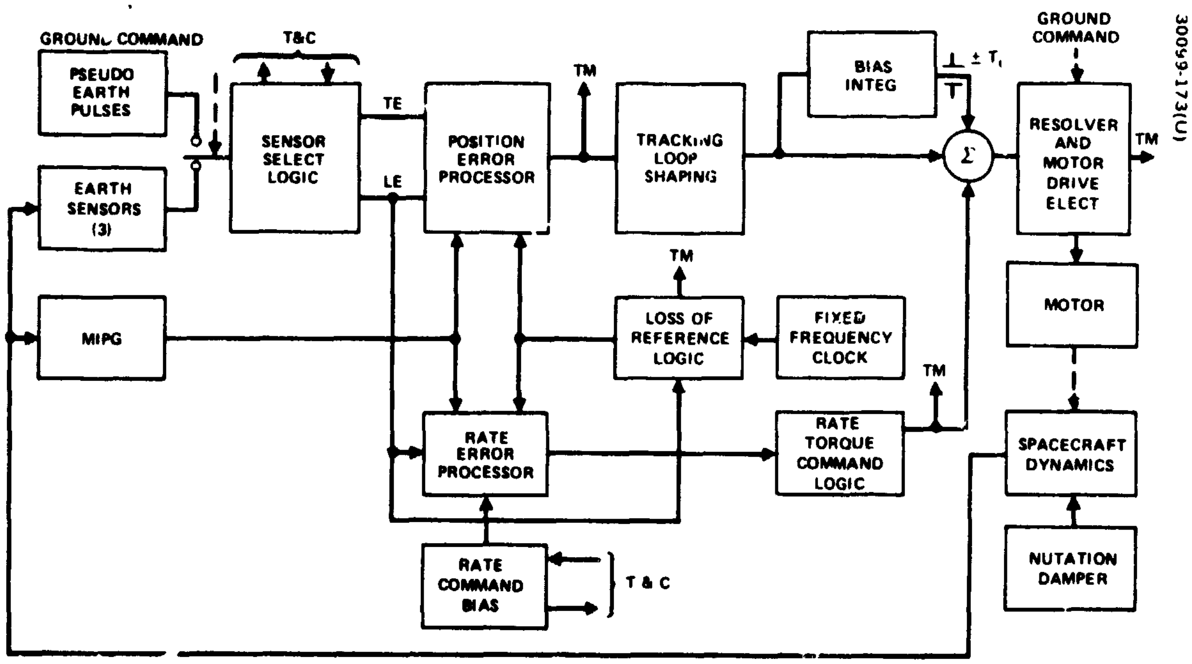


Figure 59. Despin Control Electronics Functional Block Diagram

TABLE 33. RCS ΔV BUDGET

Maneuver	ΔV, m/s	W_p, kilograms	S/C Mass,[1] kilograms	RCS I_{sp}, seconds
Spinup[2] (and orientation)	–	2.0	2098.0	225 ± 3%
Apogee motor pointing (130 degrees)	–	3.0	2095.0	180 ± 10%
Initial reorientation (120 degrees)	–	1.2	1114.8	180 ± 10%
Injection trim	55.5	31.1	1083.7	200 ± 7%
Solar torque comp (7 years)[3]	2.4	1.7	1082.0	160 ± 20%
East-west (7 years)[3]	14.9	9.1	1072.3	180 ± 10%
Station change[3]	51.2	29.6	1043.3	200 ± 7%
Contingency[4]	–	1.5	1041.8	200 ± 7%
Total RCS	128.7	79.2		
N_2 pressurant[4]		1.6		
Dry spacecraft mass (including burned-out apogee motor and N_2 pressurant)			1041.8	

(1) Assumes separated mass of 2100 kg.

(2) Moment arm = 1.38 m; all other calculations moment arm = 1.15 m.

(3) Based on spacecraft mass following station acquisition.

(4) Based upon 2 percent of propellant mass.

(5) Assumes four 30,000 cm^3 tanks; initial tank pressure = 241.3 N/cm^2 at 294 K.

Notes:

$I_{roll(separation)} = 542$ kg-m^2; $I_{roll(apogee\ motor\ burn\ out)} = 339$ kg-m^2

Solar torque = 0.133×10^{-5} kg-m

for the orbital injection maneuver, impulse for which is developed by the apogee motor. Most maneuvers will be initiated and terminated by ground command. Initial spinup and automatic attitude control will be initiated and terminated by on-board logic. Synchronizing the firing commands with sun sensor information will properly phase maneuvers. Each thruster command pulse will be 0.17 second at a spacecraft spin speed at 45 rpm and 0.08 second at 90 rpm. Table 34 summarizes the maneuvers, thruster utilization, and source of firing command.

TABLE 34. RCS MANEUVER SUMMARY

Maneuver	Thruster Used	How Initiated
Spin Speed Control		
Initial spinup	Both spinup, steady-state	Initiated by separation switch. Terminated by on-board g switch
Spinup trim	Either spinup, pulsing or steady-state	Ground command
Spindown trim	Either axial, pulsing or steady-state	Ground command
Attitude Control		
Nutation control	Either axial, pulsing	Automatic firing
Attitude drift	Either axial, pulsing	Ground command
Reorientation	Either axial, pulsing	Ground command
Velocity Control		
Stationkeeping	Either radial, pulsing	Ground command
AKM performance anomaly	Either radial, pulsing	Ground command
Booster performance anomaly	Either radial, pulsing	Ground command

Performance predictability will be as follows:

- Steady-state thrust: ± 4 percent
- Pulse mode operation:

Pulse number	0 to 10	10 to 50	50
Cumulative impulse, percent	± 20	± 15	± 10
Cumulative vector angle, degrees	± 30	± 20	± 10

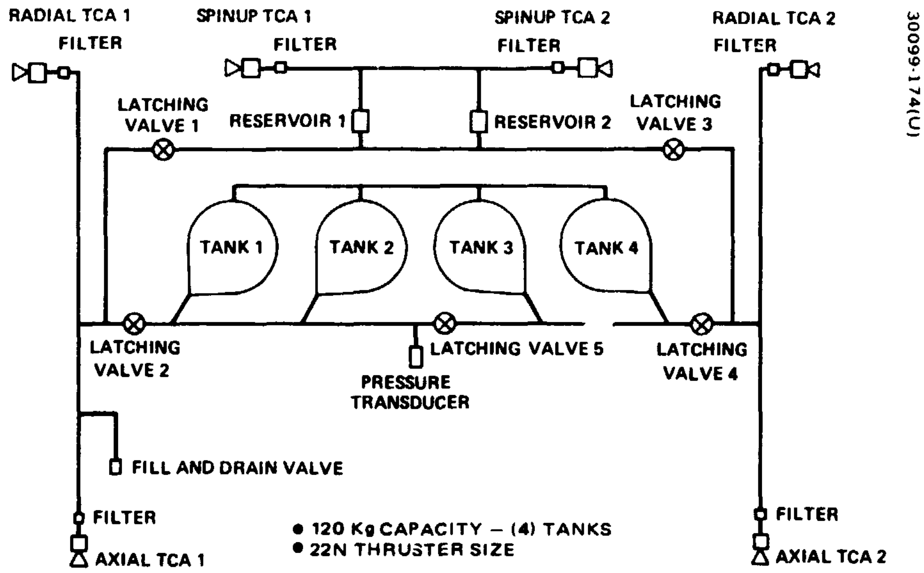


Figure 60. Reaction Control Subsystem Schematic

Positive control of spin results from biasing axial thrusters 0.5 degree (spindown). This angular misalignment exceeds the expected 3 thrust misalignment. Thus, the spin speed decrease from operation of axial thrusters will require infrequent periodic operation of the spinup thrusters to maintain spacecraft spin speed. This feature can also be utilized to decrease spacecraft spin speed.

Since a significant portion of the propellant load is contingency (for correction of 3 apogee motor and booster performance variations), it is impossible to predict the exact amount of propellant remaining at any specific time. It is anticipated that tank pressure will initially be set at 241.3 newtons/cm^2 and will decrease to 80.4 newtons/cm^2 at propellant exhaustion.

Figure 60 shows the arrangement of the RCS. It is a redundant design (except for propellant), selected to provide high reliability with a minimum of components. Malfunction of any single valve or thruster will not result in loss of any subsystem function. The RCS is assembled as a unitized, all-welded into the system by diffusion bonded, coextended titanium-to-steel transition joints. The only mechanical joints in the RCS are the thrust chamber-to-propellant valve interfaces, the propellant valve redundant seats (upstream of the previously mentioned interface), and the redundantly sealed fill and drain valve.

TABLE 35. RCS COMPONENTS

Component	Number per Spacecraft	Unit Mass, kilograms	Manufacture	Previous Program Qualifications
Thruster 22 24N	6	0 54	Hughes	HS-312
Propellant valve, all thrusters	6	Included in thruster mass	Hydraulic Research Manufacturing Co.	HS 312,HS 318, HS 333
Tanks	4	2.46	–	New component
Reservoirs	2	0.11	Hughes	HS 318
Filters	6	0.14	Vacco Industries	HS 312,HS 318, HS 333
Latching valves	5	0.27	Carleton Controls Corp	HS-312,HS-318
Fill/drain valves	1	0 18	Hughes	HS 312,HS-318, HS-333
Transducer	1	0.14	Edcliff	HS 312,HS-318, HS 333,ATS,HS-308
Lines and fittings	1	1.36	Hughes	HS 312, HS-318, HS 333
Transition tubes	17	Included in line and fitting masses	Nuclear Metals Division Wittaker Corp.	HS-312, HS 318, HS-333
Welded tees	10		Hughes	HS-312, HS-318, HS-333

Table 35 summarizes the component mass, previous use, and number required per spacecraft.

Identical thruster propellant control valves are used on all thrusters. The valve is a torque motor actuated unit which employs series-redundant tungsten carbide seats and poppets. It is of welded construction and hydrazine does not contact electrical components. It is held closed by a combination of spring forces and permanent magnet forces. When power is applied, electromagnetic forces overcome these closing forces, and the valve opens. When power is removed, the valve closes.

Redundant axial, radial, the spinup thrusters are provided. All utilize Shell 405 catalyst (Grade AGSG) to decompose the hydrazine into hot gases which are expelled through a converging-diverging nozzle to produce thrust. The thrusters are fabricated of L-605 alloy, which is resistant to nitriding and has excellent high temperature physical properties. Each has a flow trim orifice in the inlet line, which is readily removable to adjust the p of the thruster.

All thrust chambers will operate satisfactorily in either the pulse or steady-state mode. The propellant valve may be readily removed for cleaning or replacement without disturbing the thrust chamber. The nominal thrust level of each of the six thrusters used is 22.24 newtons.

The four propellant tanks operate in the blowdown mode and employ no propellant management devices. The liquid-gas interface is controlled by the centrifugal forces resulting from spacecraft spin. The tanks, made of 61 Al-4V titanium, are conispherical. A typical tank is shown in Figure 61. Each has two ports – a liquid outlet at the apex of the conical section, and a gas port, 180 degrees opposed. The included angle of the conical section is 85 degrees. This permits total removal of liquid by spinning (in orbit) or by gravity (during ground operations). At launch, each tank will contain approximately 19.4 kg of fuel, which is substantially less than the 23.0 kg for which the tank will be designed. Tanks can, therefore, be topped off to match launch vehicle payload capability at time of launch, thereby providing some excess maneuvering capability or propellant redundancy.

Each of the five latching valves is housed in a welded stainless steel body. As shown in Figure 62, a belville spring provides the force to latch the valve in either the open or closed position, after removal of power from the actuation solenoid. The valve seat is a stainless steel to teflon interface. Moving parts are isolated from propellant contact by a welded metal bellows, which also balances poppet loads. All are normally closed, except during maneuvers.

A high capacity filter, with 10 microns absolute rating, is provided upstream of each propellant valves. Figure 63 illustrates the construction of this filter. It consists of electrochemically etched discs mounted concentrically on a perforated tube. The entering fluid exist through the tortuous paths etched into the discs which are encased in a welded titanium housing.

As all propellant tank gas phases are interconnected, a single potentiometer type transducer in which pressure is sensed by an aneroid capsule of stainless steel is used. The deflection of this capsule is transmitted through a pushrod to the wiper of a linear-wound resistance element. An exploded view of this transducer is shown in Figure 64.

A single manually operated and direct acting fill and drain valve is used. This valve is shown in Figure 65. The primary seal is formed between a tungsten carbide ball and the titanium body. Since these materials permit the application of high closing torques, zero leakage is achieved repeatedly. A redundant mechanical cap seal is installed for launch.

Propellant and gas manifolds are fabricated from seamless tubing, (0.63 cm outside diameter and 0.05 cm thick walls) of 6 Al-4V titanium alloy. Branch lines are accommodated by tee fittings. Stainless steel components are welded into the system by means of transition joints. These coextrusions of 6 Al-4V titanium and 304L stainless steel provide a transition of properties from one to the other. All connections are butt-welded by an automatic tube welder that produces preprogrammed, continuous tungsten inert gas (TIG) welds without the use of sleeves, rings, or filler material.

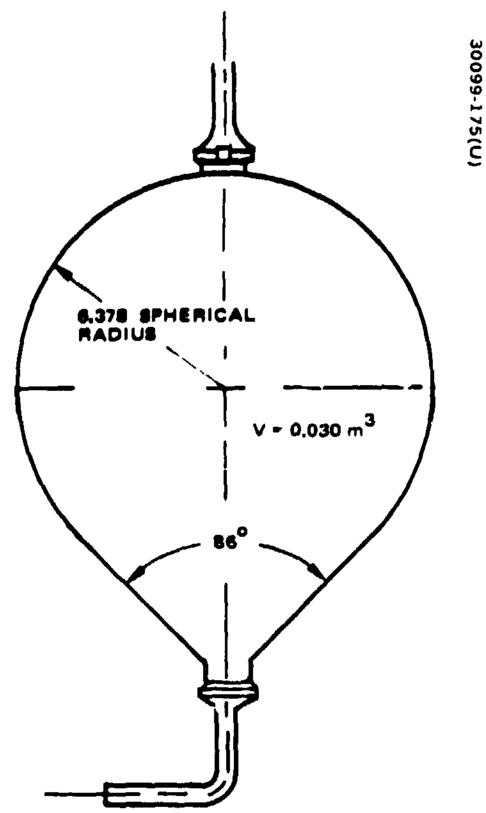
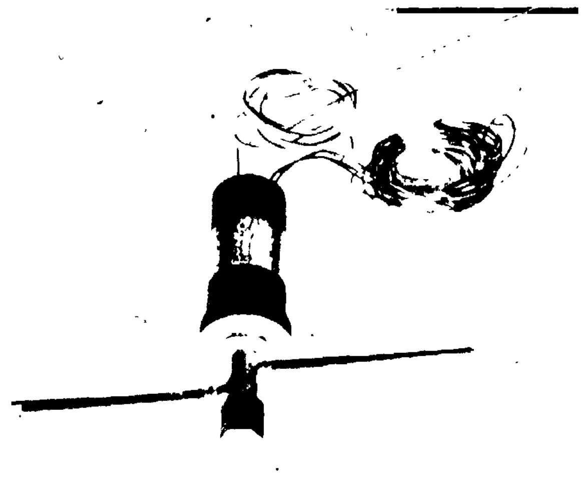
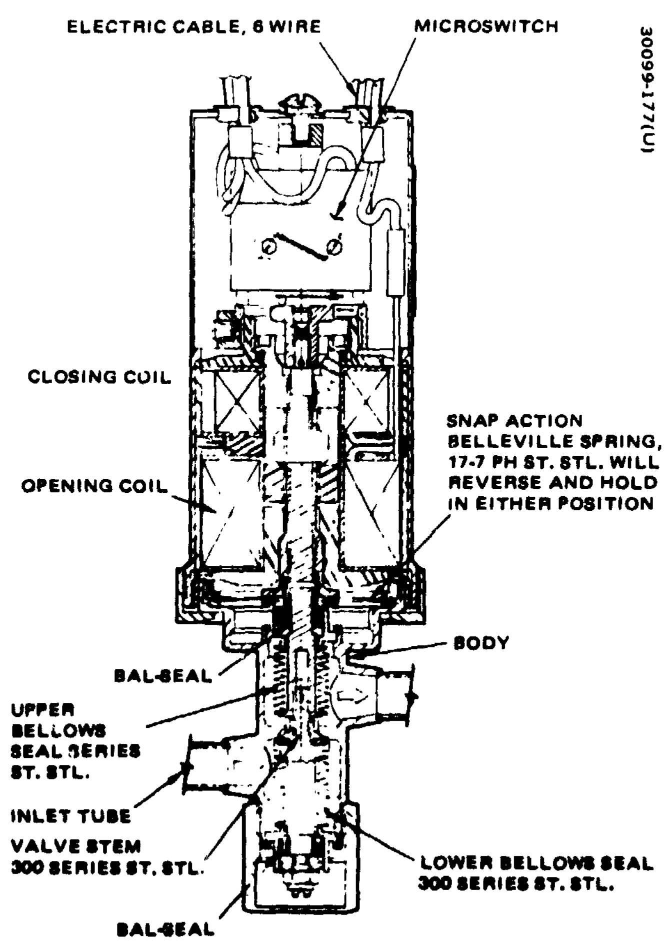


Figure 61. Propellant Tank

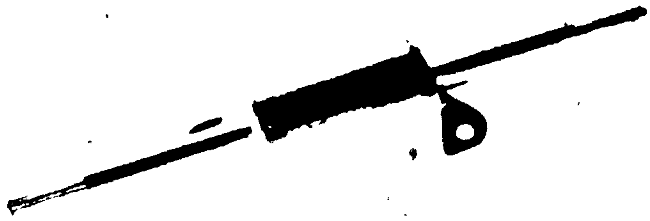


a) ASSEMBLED CONFIGURATION (PHOTO A27887)

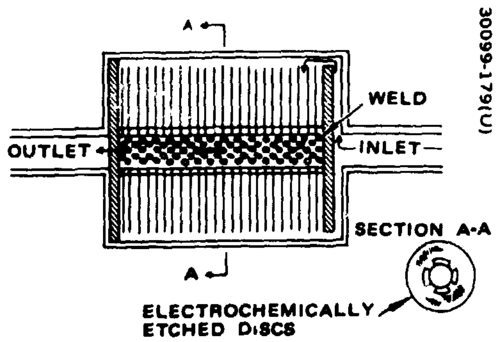


b) CROSS SECTION VIEW

Figure 62. Propellant Latching Valve



a) ASSEMBLED CONFIGURATION (PHOTO A27890)

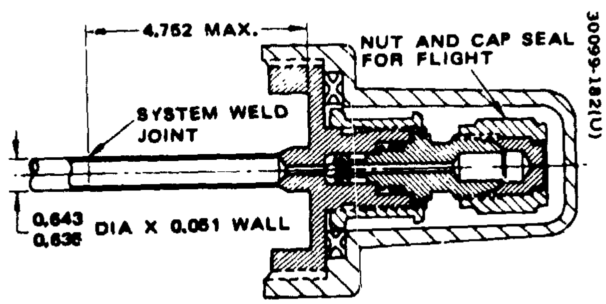


b) CROSS SECTION VIEW

Figure 63. Hydrazine Filter

Figure 64. Pressure Transducer

a) ASSEMBLED VALVE (PHOTO ES290*7)



b) CROSS SECTION VIEW

Figure 65. Fill/Drain Valve

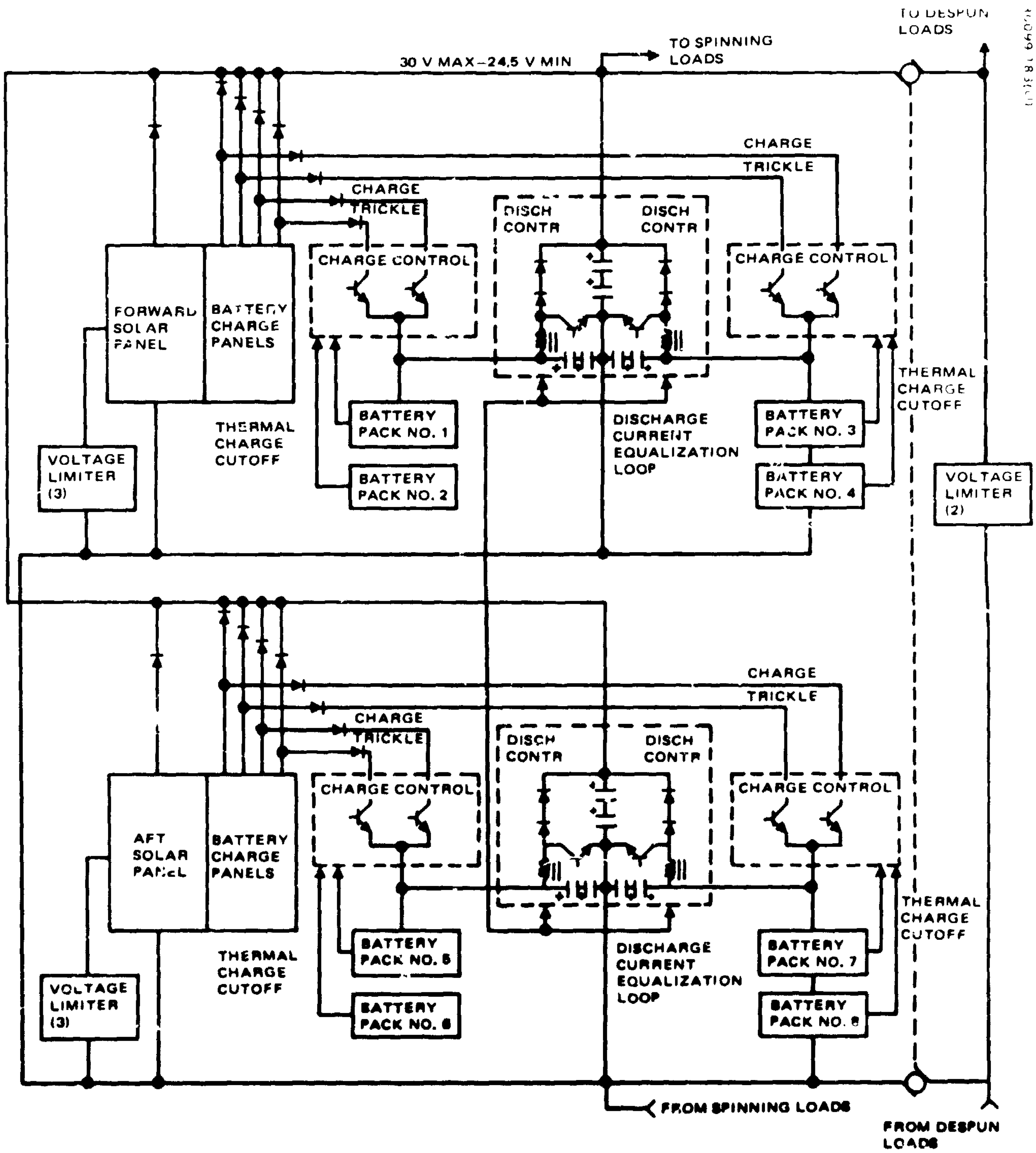


Figure 66. TDRS Power System Block Diagram

4.3.6 Electrical Power Subsystem

The electrical power subsystem supports operation of all payload and spacecraft subsystems. It is required to provide payload power continuously for a minimum of 7 years. The power requirements for the different operating modes for both the sunlit and eclipse portion of the orbit were discussed in Section 4.1.

The basic configuration of the power subsystem is shown in Figure 66. The solar array provides sufficient power to support all communication loads and also charge batteries simultaneously in eclipse season. The power subsystem has four batteries with 18 cells each. Each battery is composed of two battery packs. The cells are 20 amp-hour in size. The battery output is boosted by a boost discharge regulator to 25.5 volt nominal regulated voltage. The battery control electronics incorporates capability for battery reconditioning. During battery charging, the solar array voltage will be 27.5 volts or higher. The batteries are charged sequentially at C/15 rate. Between eclipse periods, the batteries may be trickle-charged. The trickle charge rate is C/60. The battery charge power provided by the solar array to the batteries is 73 watts per battery. The solar panel output is 752 watts at summer solstice and 800 watts 23 days before equinox.

Bus voltage limiters maintain solar panel output voltage below 30 volts independently of load after emerging from eclipse and provide a minimum heat dissipation on the despun platform during launch and orbit acquisition and also during powered down operation.

The power subsystem mass is listed in Tables 15 and 16, and design and performance characteristics are listed in Tables 36.

The solar cells are mounted on a rotating cylindrical solar panel of 2.74 meters in diameter and 3.24 meter length. The solar cells are 2 by 6 cm, 10 ohm-cm resistivity, n/p type and are 0.30 mm (12 mil) thick with 0.30 mm (12 mil) coverglass. A total of 272 cell strings are in parallel and each string is 68 cells long. The solar array design features are listed in Table 37.

Each battery operates through a separate charge-discharge control circuit. In 7 years a maximum of 650 charge discharge cycles are expected. The maximum battery depth of discharge is 48 percent with four batteries operating and 60 percent depth of discharge after a failure with only three batteries operating.

Battery charge termination is controlled by overtemperature sensing. The batteries begin charging after emergence from an eclipse and continue charging until all batteries are fully charged. A charge control electronic system as shown in Figure 67 is employed to provide for the following alternate controls:

1) Automatic recharging of the batteries on exit from eclipse one at a time with the other battery on trickle charge

2) Automatic charge termination

3) Ground control overrride for functions 1 and 2 each battery separately, and

4) Ground control of reconditioning discharge

The battery discharge controllers are illustrated in Figure 68. These controllers maintain a regulated output voltage of 25.5 volts ± 0.5 volt. The battery voltage can vary from 24.3 to 17.5 volts during discharge. The discharge current of each battery is sensed with a magnetic current sensor, and an analog output from the sensor is provided to a current comparator circuit in each battery discharge control. This circuit acts to modify control in each boost-choke stage to provide current sharing between batteries to within an allowable rating and battery depth of discharge.

Shunt tap limiters and dissipative shunt bus limiters are used in the TDRS design. Tap limiters are used to hold the bus voltage below 29.5 volts with full load applied, dumping surplus solar panel power at beginning of life by shunting or eliminating the current supplied by the tapped strings to the main bus. Tap limiters also clamp the bus at 30 volts after exiting eclipse. Six tap limiters, each shunting a separate section of the array (1/8 of total array in each section), are provided. The limiters have set points separated by 0.1 volt, so that operation is incremental.

Bus limiters place resistive loads across the bus when the bus voltage exceeds 29.5 volts. They replace some of the heat removed from the despun section during the transfer orbit, or any other time that spacecraft loads are low. Each bus limiter and its associated external load resistors dissipate a minimum of 110 watts at a bus voltage of 30 volts. Total dissipation for both bus limiters is 220 watts minimum at a primary bus voltage of 30 volts. With a primary bus voltage below 29.5 volts, the limiters are in a standby condition and dissipate a maximum of 0.58 watt.

4.3.7 Apogee Motor

A solid propellant motor is used to inject the TDR satellite into a 3 degree inclined geosynchronous orbit. The nominal velocity increment required to circularize the satellite orbit at synchronous altitude, make the required orbital plane change, is 1756 m/s. A maximum thrust of 16,500 newtons and a maximum acceleration of 70.0 m/s^2 for a spacecraft mass of 2100 kilograms at apogee motor ignition are imposed to limit spacecraft acceleration and static loads. The maximum ignition delay time of 0.300 second is easily met with conventional ignition systems. A variation limit of 0.075 second (3σ) of ignition time has been imposed. A maximum allowable case temperature of 463 K has been established to protect the spacecraft.

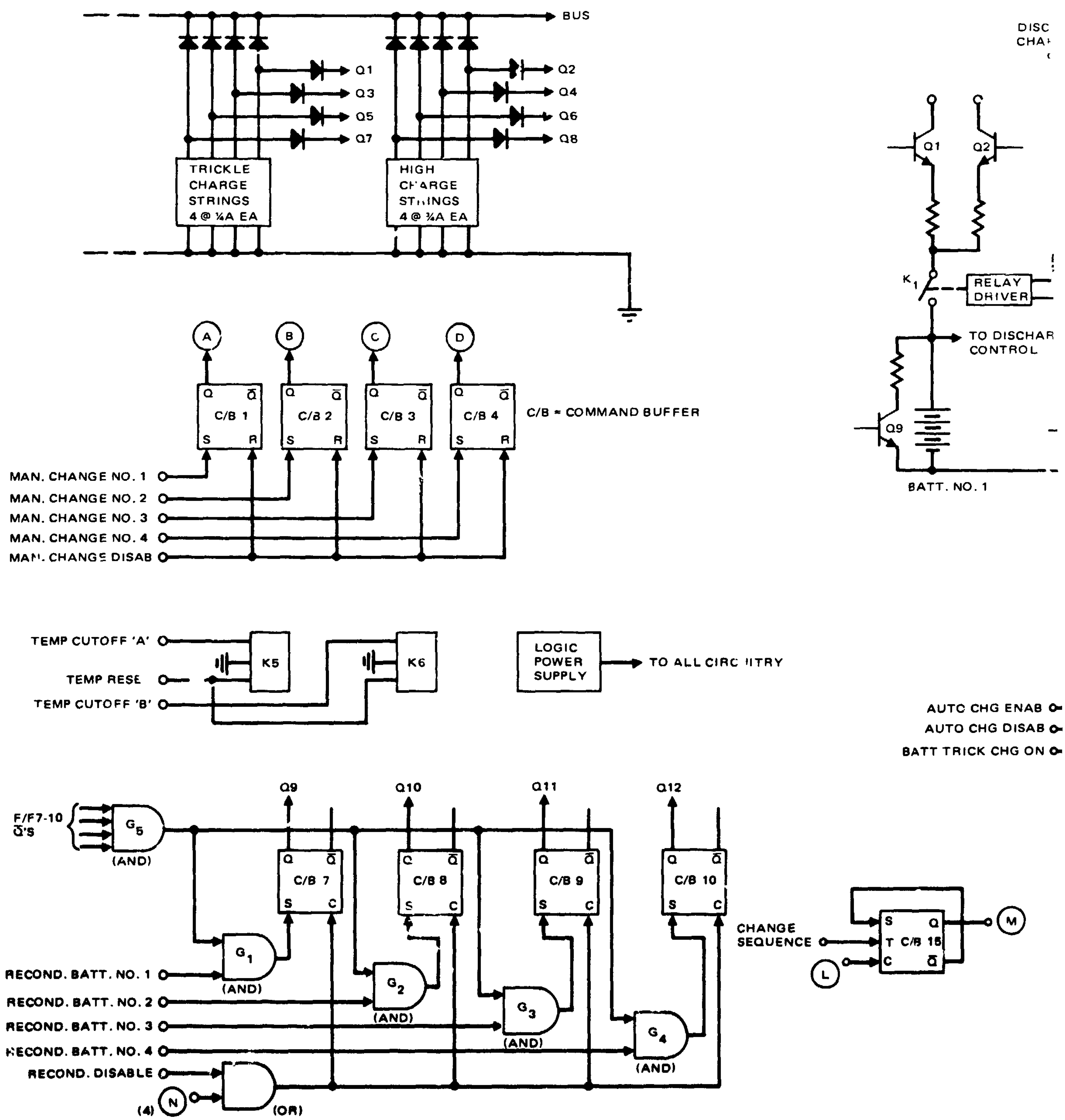


Figure 67. Battery Charge Controller Functional Schematic

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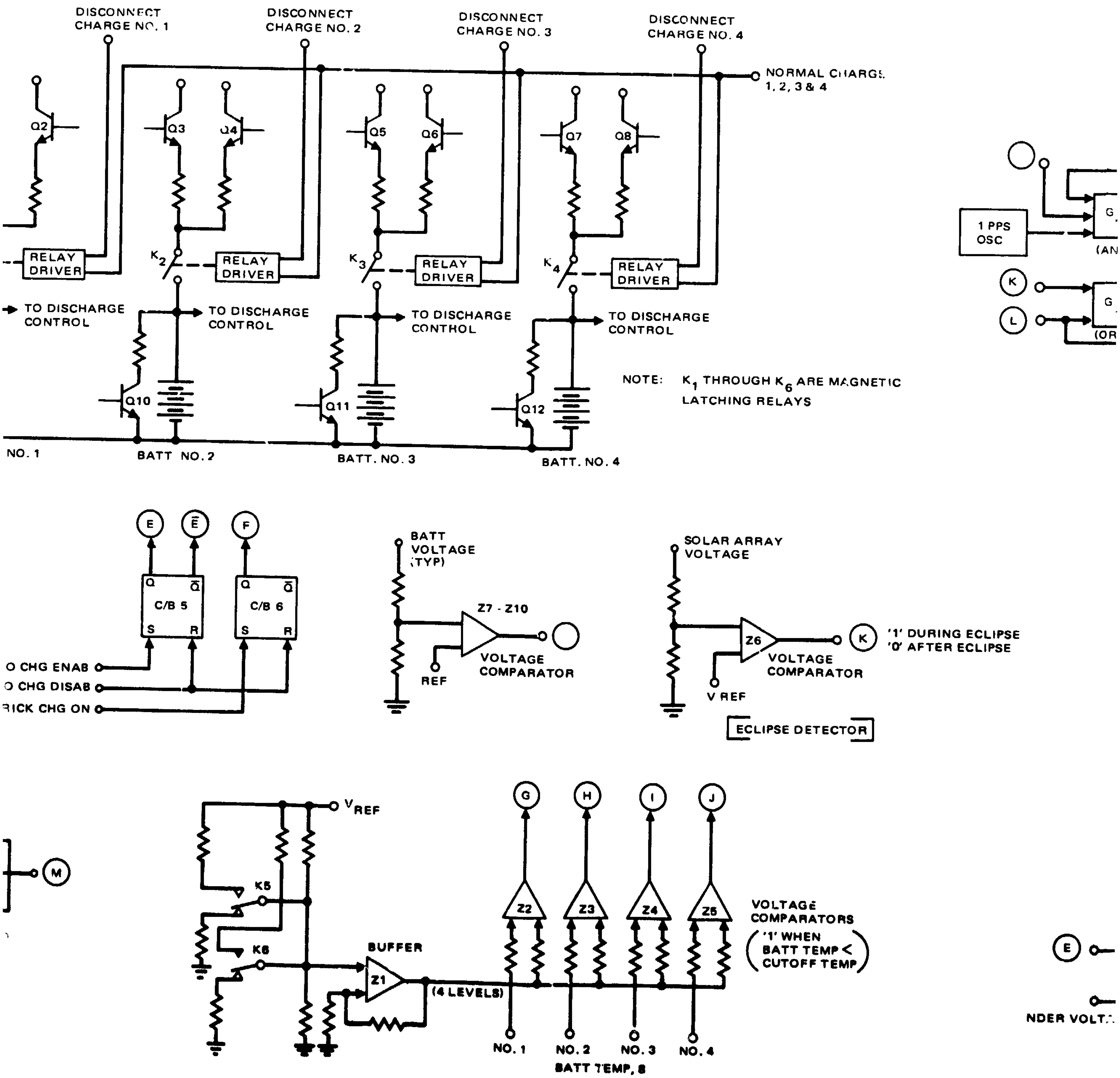

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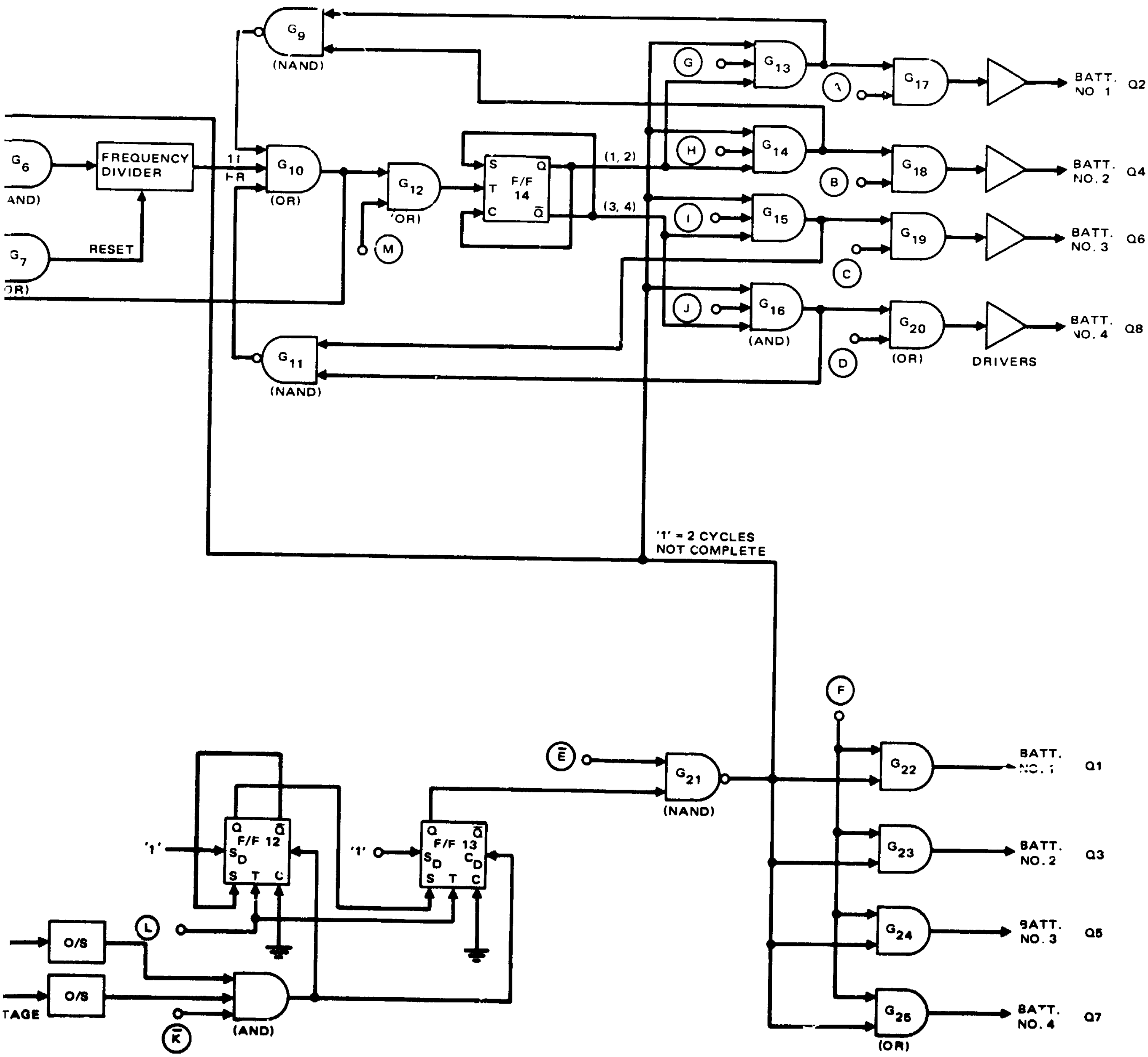

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TABLE 36. POWER SUBSYSTEM CHARACTERISTICS

Subsystem Performance	
Maximum bus voltage	30 V
Battery discharge turnon voltage	25.5 V
Minimum bus voltage, battery power	24.5 V
Solar array maximum power voltage	26.5 V
Solar array temperature	300 K maximum 183 K minimum
Solar Cell Array	
Length	3.24 m
Diameter	2.74 m
Cells	20 x 60 x 0.3 mm
Covers	20 x 60 x 0.3 mm
Available Power	
Summer solstice	752 W (end of 7 years)
Eclipse season	800 W (end of 7 years)
Batteries	
Number	Four 18 cells each
Capacity	20 A-hr
Discharge cycles	650
Maximum depth of discharge	48 percent
Charging rate	C/15
Charge termination	Temperature signal
Trickle charge rate	C/60
Cell failures permitted per battery	2
Discharge voltage	24.3 to 17.5 V
Operating temperature range	225 to 300 K
Battery Controller	
Current sharing tolerance	5 percent
Rated output current	9 A
Battery input potential	18 to 24 V
Discharge controller voltage	25 to 26.5 Volts
Charge controller operation	Automatic or ground Commanded
Discharge controller operation	Automatic
Reconditioning	On-ground command
Voltage Limiter	
Maximum bus potential	30 V
Tap limiters; operating voltage	29 to 29.5 V
Bus limiters; operating voltage	29.5 to 30 V

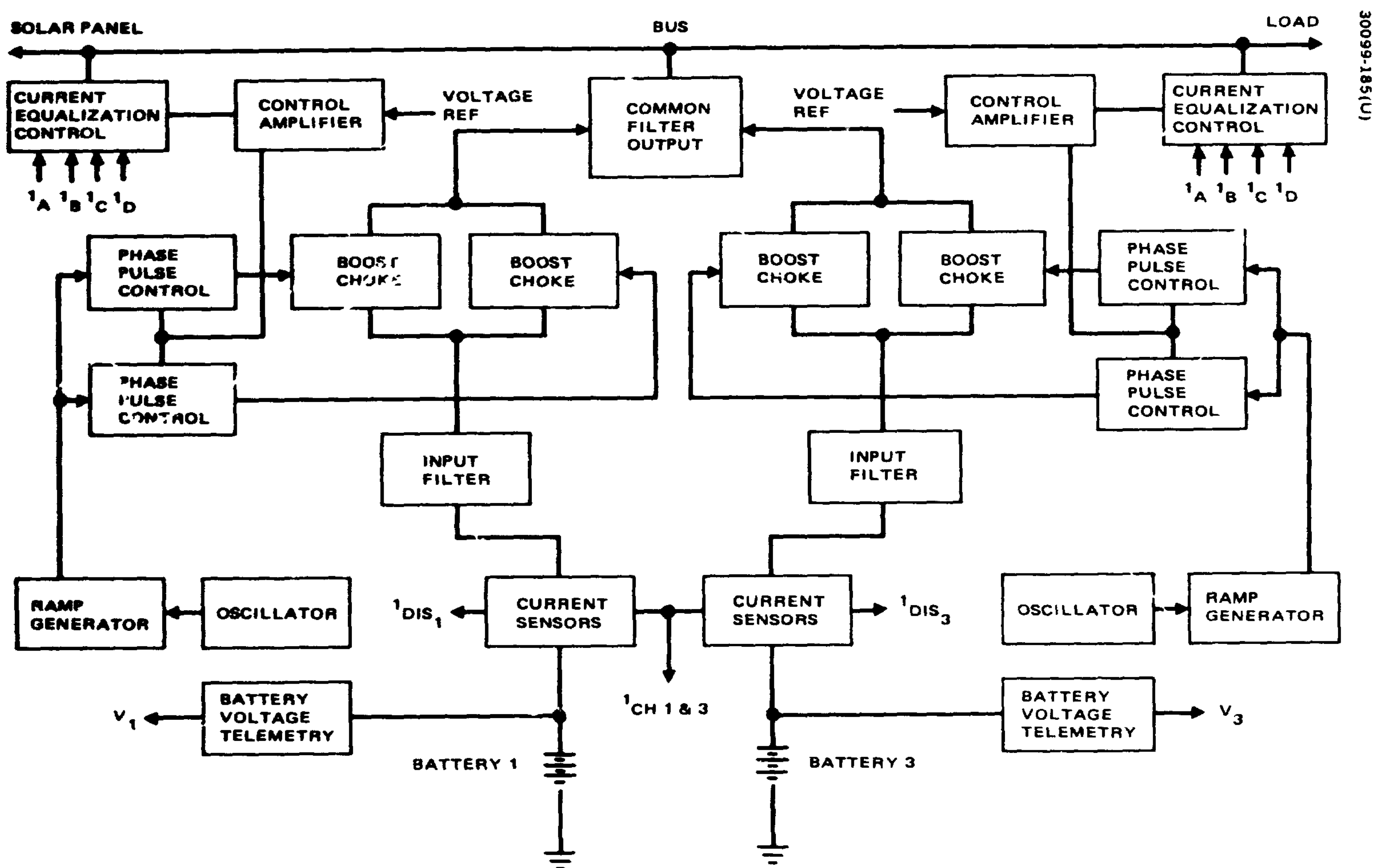

Figure 68. Battery Discharge Control Block Diagram

TABLE 37. SOLAR ARRAY DESIGN

Number of panels	1
Size	
Diameter	2.74 m
Length	3.24 m
Mass	46 kg, excluding substrate
Solar cells	2 x 6 cm, 0.30 mm thick (12 mil)
Base resistivity	10 ohm-cm
Solar cell cover	0.30 mm (12 mil) thick
Nominal cell voltage (near maximum power)	0.445 V
Nominal cell current (near maximum power)	0.411 A
Temperature	Function of location and season
Radiation degradation	
Current	0.879
Voltage	0.928
Fabrication loss	
Voltage	1.00
Current	0.98
Ripple	0.98
Effective illuminated area in current	0.318
Curvature edge defects, current	0.962
Solar angle	±26.5 degrees
Seasonal intensity	
Summer solstice, current	0.888
Autumnal equinox, current	0.993
23 days before autumnal equinox, current	0.969
Transmission loss, current	0.98
Diode drop	0.8
Panel harness drop	0.14 V

The performance, environmental, and physical requirements are shown in Table 38. The operating temperature range was established at 283 to 311 K and at 272 to 328 K for qualification.

The apogee motor is used to circularize the spacecraft orbit at synchronous altitude from the transfer orbit and to remove the orbit inclination. Final orbit trimming, if required, is accomplished by the reaction control subsystem.

The motor ignites at transfer orbit apogee by a ground command that triggers the squib driver circuits in sequence. It will burn for 49.2 seconds with an average thrust of 67,300 newtons. It is protected from accidental ignition during launch preparation and mating with the spacecraft by a safe and arm device, which both mechanically and electrically interrupts the ignition sequence.

Before ignition, the motor temperature is kept between 283 and 311 K by a kapton thermal blanket and a nozzle throat heater. Maximum motor temperature during and after firing is 463 K to protect the spacecraft.

The apogee motor design is shown in Figure 69. This motor is an offloaded Thiokol TE-M-364-4 motor. The chamber is an elongated spherical pressure vessel made from 6Al-4V titanium alloy. The case has a major diameter of 96.37 cm (attachment flange diameter) and an overall length of 125.10 cm and a mass of 34.6 kg. It consists of two hemispherical domes, tungsten-inert gas welded to a cylindrical center section. Integral attachment interfaces are provided for a light payload, for a heavy payload, and for the installation of the rocket motor into a spin table.

The rocket motor case is internally insulated to provide thermal protection for the pressure vessel during motor operation and to maintain the external surface of the rocket motor case below 590 K during motor operation and postfire thermal soak. This is accomplished by the use of forward and aft insulation assemblies and a cylindrical insulator located between the forward and aft insulation assemblies. The insulator assemblies incorporate stress relief boots in the head and aft ends of the rocket motor to provide stress relief of the propellant/liner/insulation interface during the propellant cure and thermal cycling. Positive relief is maintained by the use of a teflon sheet and teflon tape in the relief areas.

The insulation material used is TI-R-300, an asbestos-filled polyisoprene rubber. The insulation assemblies are bonded to the internal surfaces of the motor case with a rubber adhesive system and cured in place under pressure and elevated temperature.

The rocket motor has a high expansion ratio (31 to 1), composite plastic contoured nozzle. It has an overall length of 74.4 cm, of which 31.2 cm are submerged within the rocket motor chamber. The nominal diameters of the throat and exit plane are 10.92 and 60.45 cm, respectively.

TABLE 38. APOGEE MOTOR REQUIREMENTS

Performance	Requirement
Overall	
Total impulse (ΔV, m/s)	1756 ± 1% (3σ)
Maximum thrust	76,500 N
Maximum acceleration	70.0 m/s^2
Ignition time	0.300 s maximum and 0.075 s deviation (3σ)
Chamber pressure	No inflections at burnout
Maximum external case temperature	463 K
Environmental	
Operating temperature	283 to 311 K
Flight condition	Any attitude
Spin condition	70 ± 25 rpm
Time in space	10 days
Storage life	5 years
Transportation	Truck, rail or air
Vibration, maximum	
Random	TBD
Sinusoidal, maximum m/s^2 rms and frequency	TBD
Acceleration	TBD
Axial	TBD
Lateral	TBD
Physical	
Maximum mass	1060 kg
Static balance	
Loaded	18.0 kg-cm
Burned out	9.4 kg-cm
Dynamic balance	
Loaded	338.2 $kg\text{-}cm^2$
Burned out	173.6 $kg\text{-}cm^2$
Thrust misalignment	
Displacement	0.051 cm
Angular	0.002 cm/cm
Moment of inertia (roll/pitch)	Known within ±5%
Load factors	
Ultimate strength	1.15
Yield strength/maximum	1.25
Proof pressure/MEOP	1.05
Burst pressure/MEOP	1.40

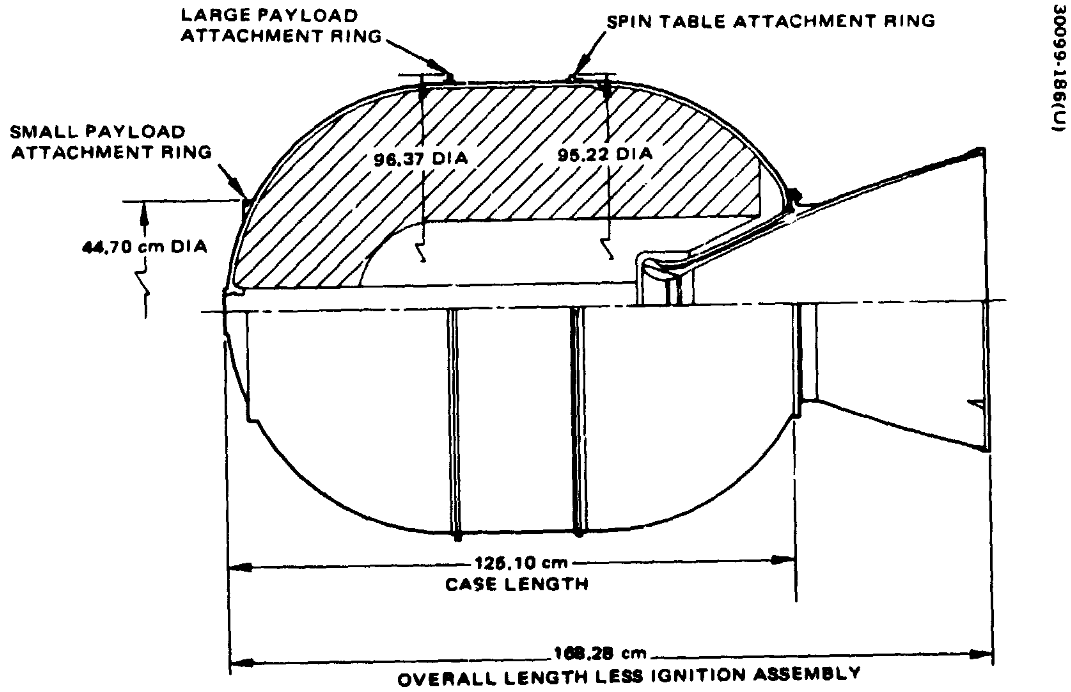

Figure 69. TE-M-364-4 Apogee Motor Envelope Dimensions

The composite plastic nozzle uses carbon cloth/fiberglass phenolic materials as the structural member, an asbestos phenolic material to provide thermal protection to the structure within the rocket motor case, a carbon-cloth tape-wrapped exit cone, a carbon-cloth rosette throat backup structure, a throat insert of Graph-I-Tite G-90, and a titanium-alloy closure ring bonded to the exit cone, which attaches the nozzle to the rocket motor case.

The ignition system is a squib-actuated, pyrogen igniter equipped with an electromechanical safe and arm device located at the forward end of the motor.

Table 39 is a summary of motor ballistic parameters at a nominal operating temperature of 297 K. Table 40 shows the calculated prefire mass of the major components. During firing, an estimated 5.5 kg of inert mass will be expended. A mass fraction of 0.93 for a motor of this size and a demonstrated propellant specific impulse of 286 seconds assures that this estimate will be met.

The apogee motor mechanical interface is through two attachment flanges. A small, 45.72 cm diameter payload attachment interface, located on the head end of the case, is a continuous ring with 24 equally spaced, holes located on a 44.70 cm diameter. A large 96.37 cm diameter payload interface is a ring on the cylindrical section of the case aft of the forward weld. The payload may be attached using 24 or 48 of the 48, equally spaced, through-holes. The tolerances of both mating surfaces will be held very tight to minimize dynamic and static imbalance.

4.3.8 Spacecraft Structure

The spacecraft structure provides the load paths and mounting surfaces needed to assemble all satellite communication and control subsystems into an integrated system. It also provides control surfaces where needed to protect components against irradiation and to regulate temperatures.

TABLE 39. AKM BALLISTIC PERFORMANCE

Parameter	Nominal Motor
Vacuum specific impulse	286 s
Vacuum total impulse	280,480 kg-s
Average vacuum thrust	67,300 N
Maximum vacuum thrust	76,500 N
Average chamber pressure	380 N/cm^2
Maximum chamber pressure	411 N/cm^2
Burn time	49.2 s
Ignition time	0.222 s

TABLE 40. MASS AND POWER SUMMARY

Component	Mass, kilograms	Power, watts
Chamber (including attachment flange)	34.6	
Insulation	15.3	
Nozzle	28.6	
Igniter (including safe and arm)	3.2	126 each squib for 0.010 s)
Heaters	(Mass included in thermal control)	
Total inert	81.7	
Propellant	980.7	
Total motor	1060.0	
Total burned out	76.2	

The primary objective in the spacecraft structure design is the attainment of a minimum mass construction consistent with adequate strength and stiffness. Stiffness must be sufficient to prevent excessive deflections that produce contact among elements in the spacecraft or with the walls of the shuttle payload bay. Based on previous Hughes experience, an on-orbit spacecraft frequency of greater than 3 Hz is desirable to avoid dynamic coupling at the spacecraft spin rate of about 1 Hz. Similarly, during boost a minimum structural frequency must be maintained to limit dynamic load amplification and coupling with the launch vehicle control system. This minimum frequency has not yet been defined for the Space Shuttle launches.

The structure must possess sufficient strength such that it will experience neither excessive or permanent deformations in the appropriate design environments as listed in Table 41. It must also be designed to withstand simultaneously the ultimate loads, applied temperature, and other accompanying environmental phenomena without failure or excessive deformation. The load factors applicable in the preliminary design or primary load carrying structure are shown in Table 42. These load factors are considered to be conservative. Validation of the structure design for flight requires detailed coupled boost vehicle/spacecraft transient load analyses.

The spacecraft structure that evolved through configuration studies for shuttle launched TDR satellites is illustrated in Figure 70. This spacecraft design employs the standard Hughes Gyrostat stabilization technology. A central thrust tube similar to that of the Intelsat IV spacecraft provides the essential primary load carry structure. Two Marman clamps provide

TABLE 41. MECHANICAL ENVIRONMENTS FOR STRUCTURAL DESIGN

Launch and Ascent Environments
Steady acceleration due to thrust and maneuver forces
Transient loads due to launch release and vehicle stage startups and shutdowns
Vibration and acoustic noise of liftoff and during maximum dynamic pressure and transonic flight
Apogee motor firing
Orbit Phase Environments
Ejection from shuttle payload bay
Spin acceleration
Reaction control forces (including failure modes)
Deployment forces of the antenna and feed
Thermal gradients and temperature cycling
Meteoroid environment
Radiation environment
Test Environments
Static qualification test
Modal survey
Sinusoidal vibration
Acoustic qualification/acceptance testing
Pyro shock test
Random vibration test for components
Acceleration test for components
Solar thermal-vacuum/thermal-vacuum tests (thermal stresses)
Ground and Prelaunch Environments
Horizontal and vertical spacecraft assembly handling
Vibration due to air and truck transportation
Shock due to drops during handling

TABLE 42. STRUCTURAL LOAD FACTORS

Strength Requirements	Longitudinal Load Factor	Lateral Load Factor
Shuttle boost	+3, -1	±0.5
Transtage boost	+2, -1	±0.2
Apogee motor boost	±8	1.25R
Ground handling	±2.0	±2.0

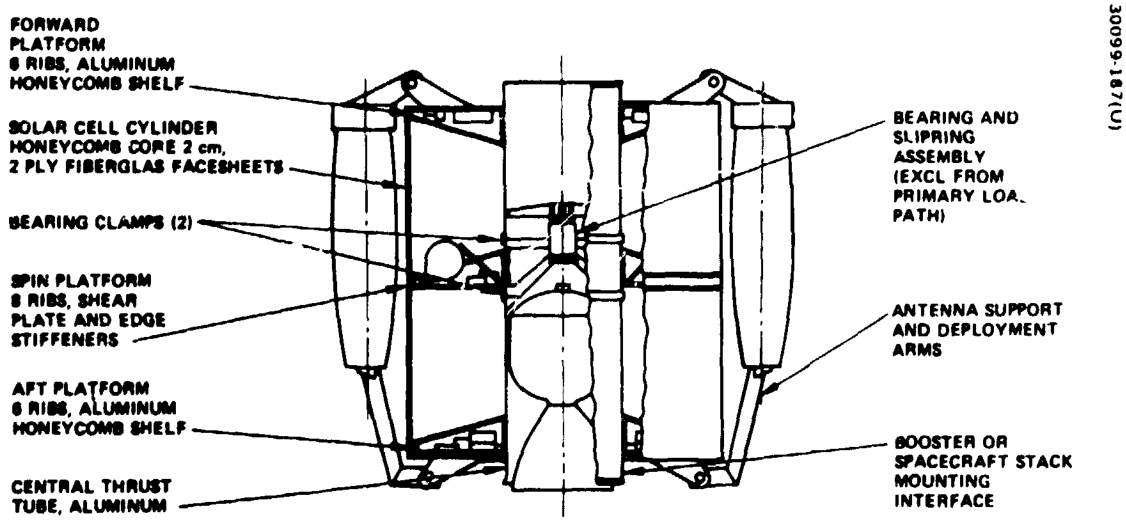

Figure 70. Primary Spacecraft Structure

load transfer during boost, transfer orbit and synchronous orbit injection. When these clamps are released on orbit, the forward and aft thrust tube sections remain connected through a 150 mm diameter shaft. The middle tube section is free to rotate about the shaft on a bearing assembly.

The middle thrust tube section forms the core of the spacecraft spin assembly. Eight radial ribs span from the thrust tube to the cylindrical solar panel substrate of 2.75 meter diameter. This major loading results from carrying the solar panel substrate at the tips of the ribs and four RCS propulsion tanks at midspan. Additional loading is generated by batteries, electronic equipment, and sensors, which are mounted on the spinning shelf. The shelf is an annular honeycomb platform around the thrust tube that is fastened to the spin ribs and provides torsion rigidity to the spacecraft spin assembly.

The spinning cylindrical substrate provides mounting surface for the solar cells and a protective irradiation shield for the satellite equipment. The substrate is about 3 meters long and it is constructed as a 2.5 cm thick aluminum honeycomb sandwich with two-ply fiberglass facesheets.

The despin spacecraft structure assembly consists of the rigidly connected forward and aft equipment platforms and antenna support masts. The equipment shelves are of honeycomb sandwich construction and are supported off the central thrust tube sections by radial ribs. These ribs are riveted assemblies of aluminum sheet and angle sections.

The central thrust tube and despun platform connecting shaft form a redundant load path during spacecraft launch and ascent. The central thrust tube is rigid as compared to the shaft and therefore provides the primary load path during launch and apogee motor burn. On orbit and after

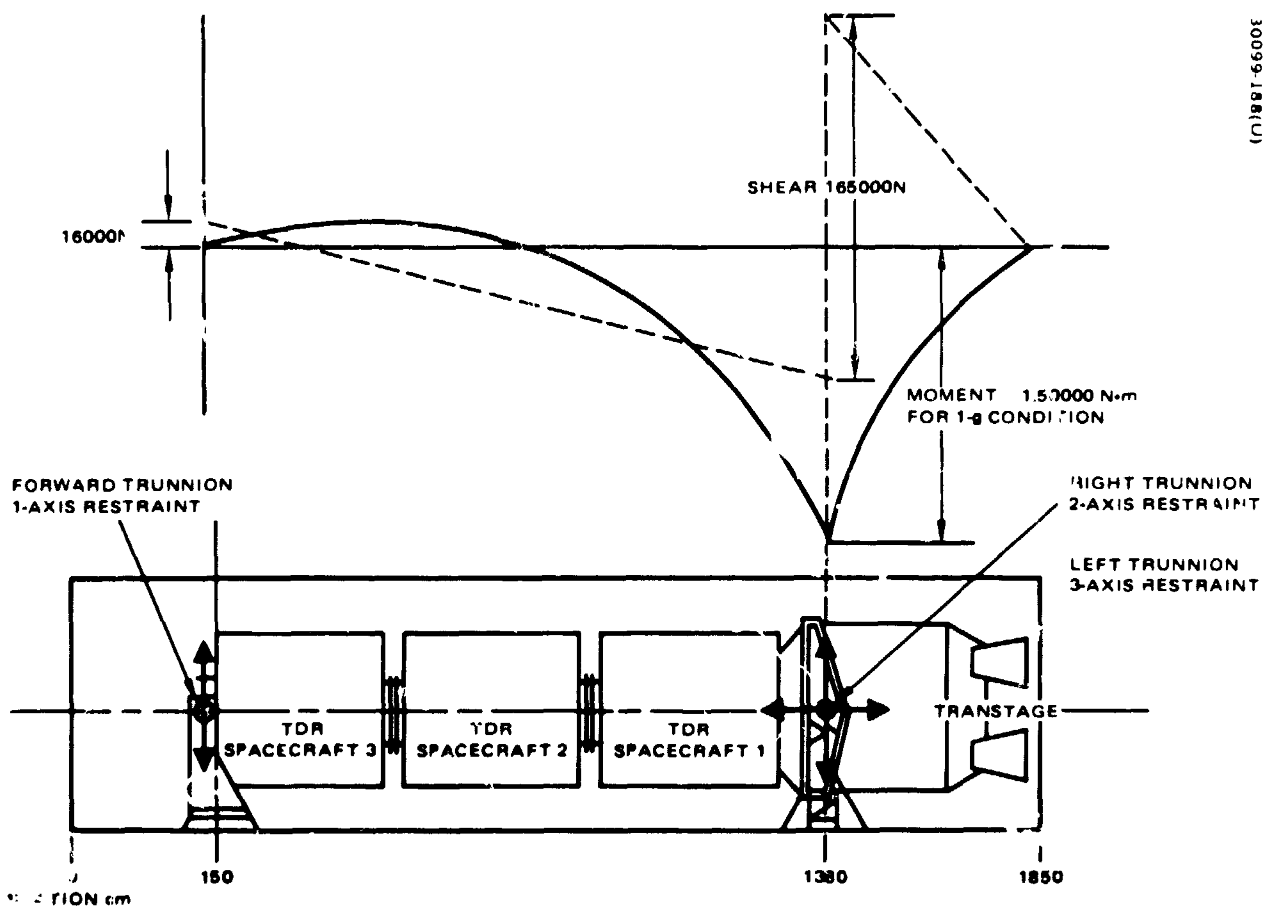

Figure 71. Moment and Shear Force Diagram for Horizontal Spacecraft Assembly

release of two bearing clamps, the relatively small spacecraft maneuver loads and antenna deployment loads are transferred through the spacecraft central spin bearing assembly.

The thrust tube is a riveted assembly of aluminum skin, stiffeners and rings whose minimum diameter is determined by the apogee motor size. The required cross-sectional area of the stiffened circular cylinder was computed for a bending moment of 3×10^5 N-m. This loading is conservatively predicted for the tandem assembly of three spacecraft forward of the Transtage booster and for support of the complete assembly in its horizontal position from three trunnions in the shuttle by sidewalls. The moment and shear force diagram for this support configuration is illustrated in Figure 71 for the 1 g environment. The minimum lateral frequency of the assembly is estimated to be about 2 Hz. Additional support ports are indicated in the shuttle payload design manual; these will be utilized when a higher lateral structure frequency is required.

The individual spacecraft and the tandem stack of three satellites are tied for launch by Marman bands of Intelsat IV type. A frustum adapter cone provides the load path from the thrust tube to eight Transtage support fittings. Compression springs in between the individual spacecraft as well as the Transtage adapter depart energy upon sequential release of the Marman clamps for proper satellite separation before apogee motor ignition.

The assembly of communication antennas is stowed alongside the solar panel cylinder for launch. All antennas are rigidly tied down at both ends to their deployment arms and the despun platform. No cantilevered support is used during periods of intense spacecraft loading. On-orbit pin pullers are activated by ground command and the antenna reflectors are deployed by simple rotary linkage motion and locked in position. Since the deployment arms also provide antenna support, they are dimensioned for sufficient rigidly to avoid coupling with the spacecraft spin rate of about 1 Hz.

Types of construction for major structural elements and their materials are listed in Table 43. Most components employ proven Hughes design concepts. The through-shaft in the bearing assembly is an exception; however, it has to function as primary structure member only on orbit when the loading is small.

TABLE 43. STRUCTURAL ELEMENTS

Item	Type of Construction	Status
Central thrust cone (aluminum magnesium)	Cylindrical and conical sections with mating end rings and hoop stiffeners	Intelsat IV design
Spun platform (aluminum)	Eight tapered ribs connected by a 0.05 cm thick circular plate and intercoastals	Intelsat IV type
Solar array substrate (fiberglass)	Two 3 m diameter, by 1.50 m long sandwich cylinders 2.5 cm aluminum core, two-ply facesheet	Intelsat IV type
Despun platform (aluminum)	1.25 cm thick sandwich discs separated and supported by six radial ribs of 30 cm depth	Intelsat IV design; modified for TDRS equipment mounting
Antenna support (aluminum)	Tubular mast and deployment arms, deployable truss Astromast for aft mounted antennas	New design
Bearing clamp (steel)	Marman band	Modified Intelsat IV design

Satellite shipping, assembly for loading into the shuttle bay, unloading on orbit, and sequential spacecraft deployment are illustrated in the Figure series 72 through 76. The spacecraft are assembled and individually crated for shipment in upright position. In order to accommodate loading into the shuttle bay, three spacecraft and the Transtage booster are aligned horizontally on ground supports and tied with three Marman type clamps at the central thrust tube. The complete assembly is then lifted by crane into the shuttle payload bay where it rests and anchors on trunnion supports. On the launch pad, the shuttle/booster are erected vertically. A simple parallel linkage mechanism heaves the payload module clear of the Space Shuttle in the parking orbit. After transfer orbit injection burn of the Transtage booster, the three spacecraft are sequentially separated and spun up via its RCS system to provide stabilization during apogee motor burn. Once on orbit, the two bearing clamps are released and the forward and aft spacecraft platforms are despun while the spin rate of the spacecraft spin section increases as defined by the law of conservation of total system momentum. Unlatching and positioning of all communication antennas will ready the satellite for mission use.

4.3.9 Thermal Control

The spacecraft thermal control system must provide an adequate temperature environment for all satellite subsystems during a mission life of 5 years in synchronous orbit. The orbital design must be compatible with survival and/or operation of all subsystems during transfer to synchronous orbit, apogee motor burn, and on-orbit operations. Table 44 presents the subsystem temperature requirements that have been established for the TDRS. Table 45 outlines the expected extremes in system power dissipation using baseline estimates of equipment power requirements.

The overall thermal design concept employed for TDRS is one of passive thermal control, which takes advantage of both the temperature averaging that results from the uniform spin rate of the vehicle solar panel and the containment of the sun within ±23 degrees of the orbit plane. The key features of the thermal design are identified in Figure 77. Radiation is the dominant mode of heat transfer between major spacecraft elements. The temperatures of the spinning structure and low power dissipation regions are controlled by maximizing the radiation coupling to the solar panel. The batteries are hard-mounted to the structural ribs in order to provide thermal fin capability. The lines and valves of both the axial and radial thrusters are provided with molded blanket heaters (a heater system of 0.03 W/m propellant line and 0.75 watt per thruster is used) that prevent any portion of the system from reaching the freezing point of hydrazine at any time during the operational life of the spacecraft. These heater elements are wrapped with low emittance aluminum tape to minimize the heater power requirements. During eclipse the hydrazine tanks are maintained above the freezing point with multilayer insulation.

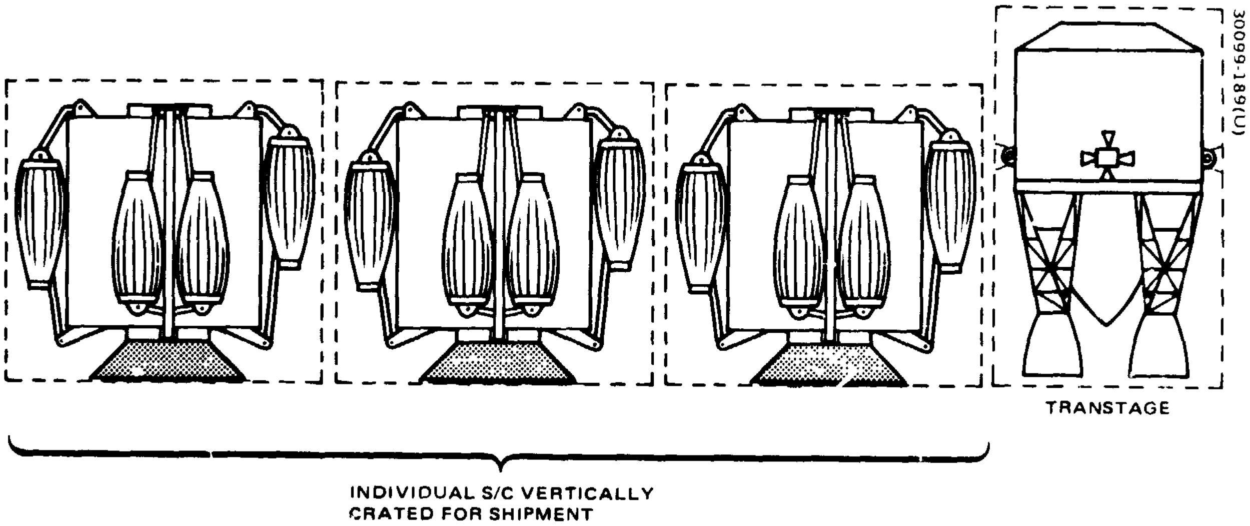

Figure 72. Shipping Configuration

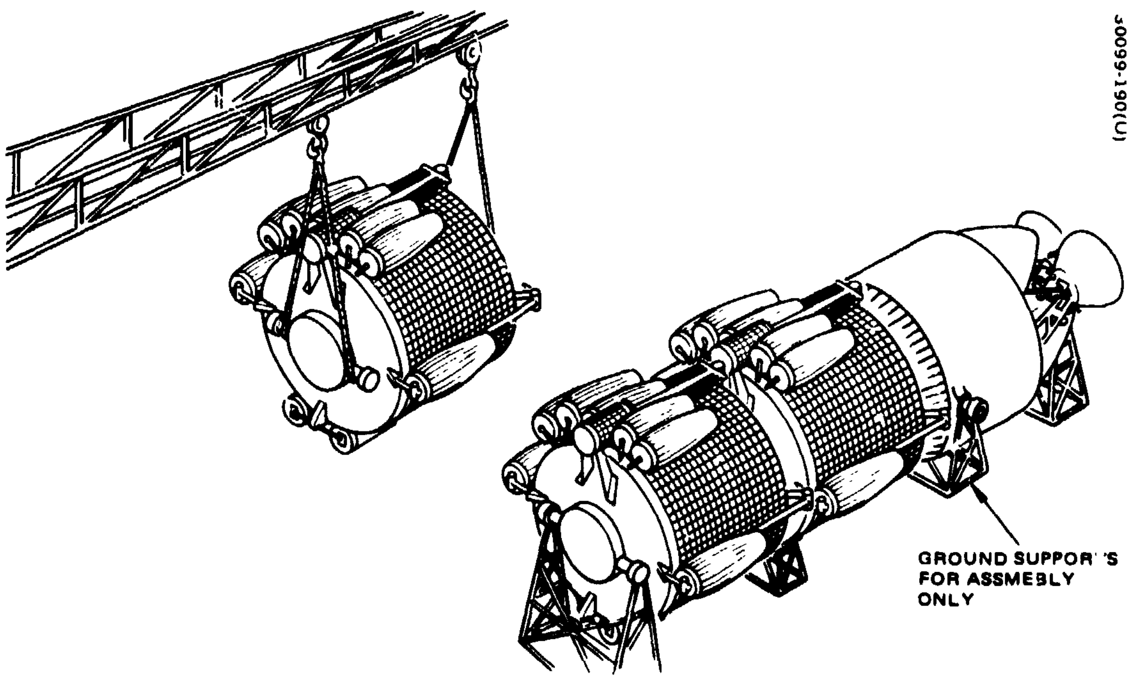

Figure 73. Horizontal Assembly for Loading Into Sh:.ttle Bay

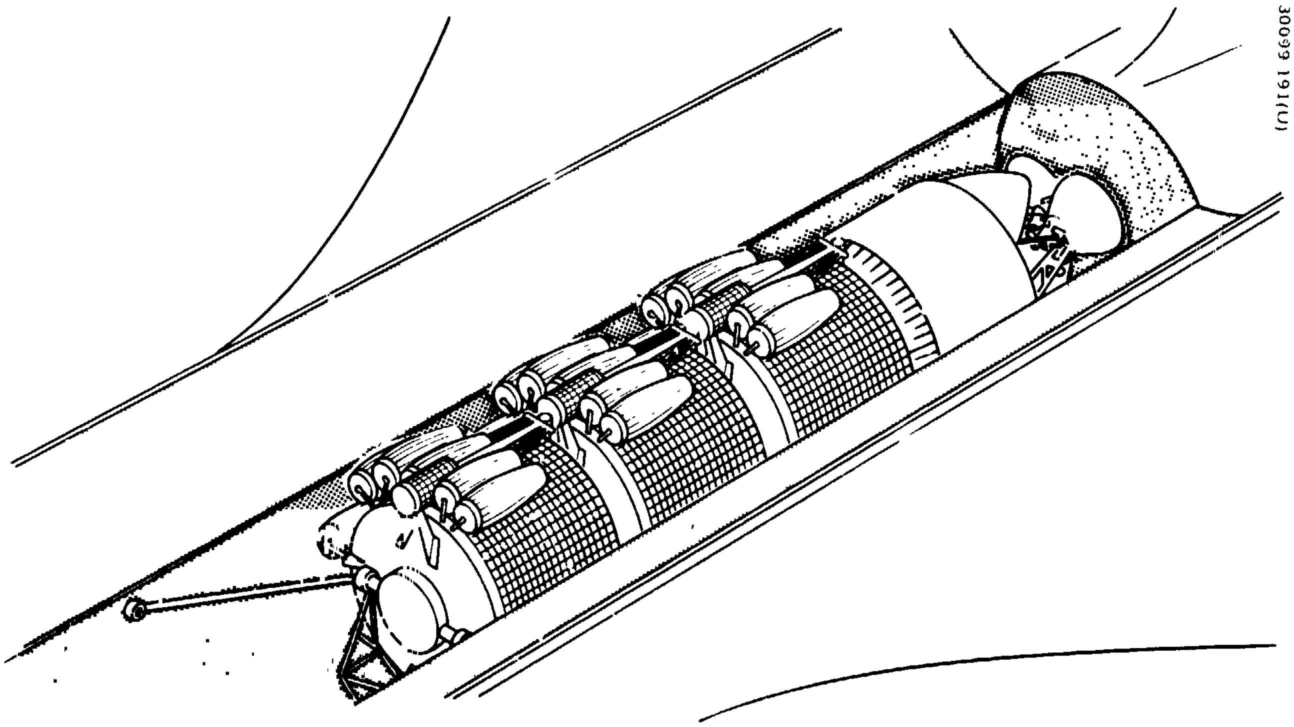

Figure 74. TDRS Assembly in Shuttle Bay

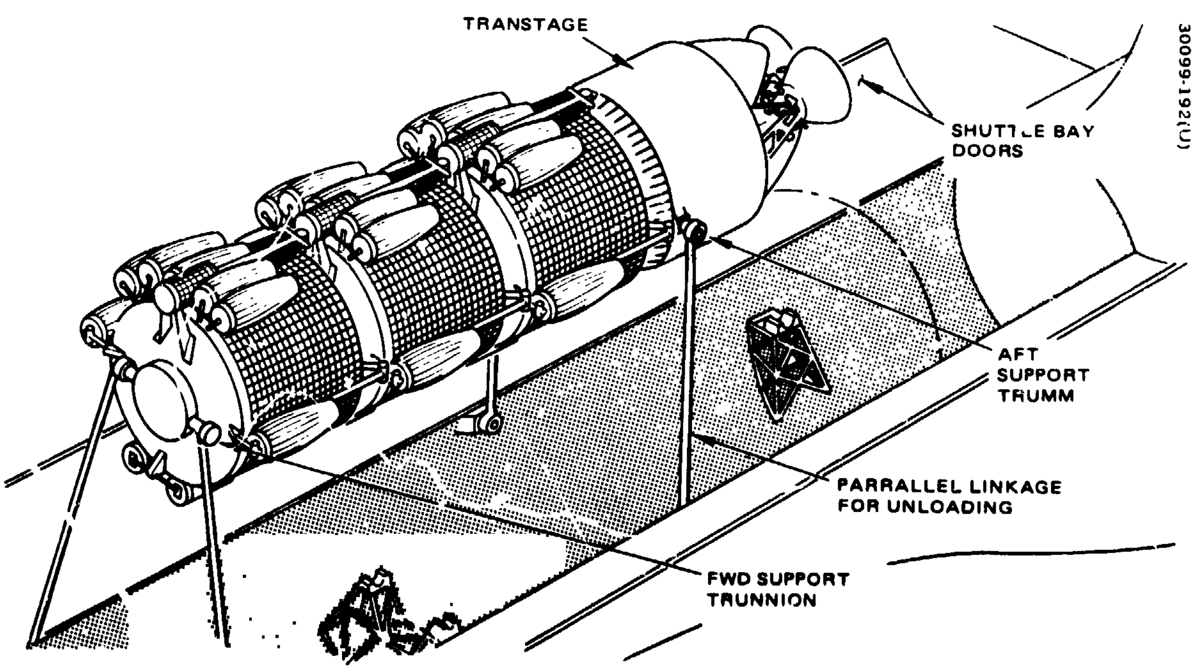

Figure 75. TDRS Deployment from Space Shuttle

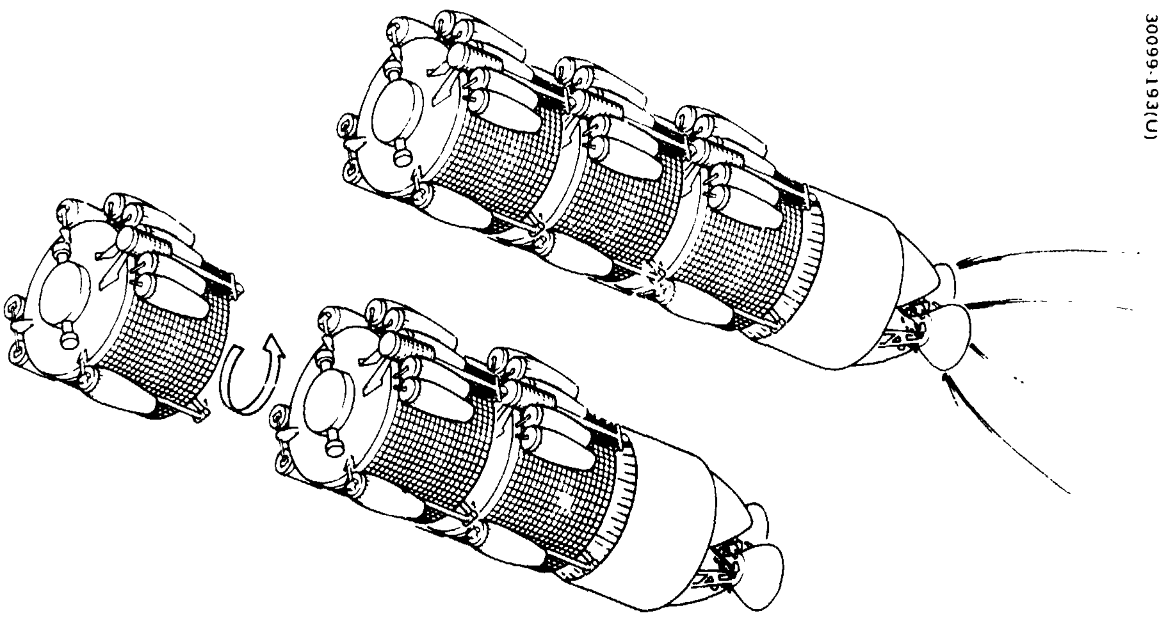

Figure 76. Transfer Orbit Injection, Spacecraft Separation and Spinup

TABLE 44. SUBSYSTEM TEMPERATURE REQUIREMENTS

Equipment	Design Range, K	Eclipse Minimum, K	Comments
Despun			
Transmitters, receivers and other repeater electronics	267 to 311	261	Design limits used in the successful qualification and flight application of similar communication electronic equipment
Telemetry and command electronics	267 to 311	261	
Antenna positioner	222 to 367	222	Identical to Intelsat IV design limits
Antenna mast and cabling	200 to 367	200	
VHF and S band antenna	117 to 395	117	
Spinning			
Apogee motor	278 to 306	278	Thiokol motor design limits
Despin bearing	273 to 311	284	
Despin electronics	267 to 323	261	Intelsat IV
Batteries	273 to 300	273	No overcharge
Solar panel	222 to 297	172	
RCS tanks	278 to 333	278	Intelsat IV design with active heating of lines and valves
Lines	278 to 367	278	
Valves	278 to 339	278	

TABLE 45. SPACE SHUTTLE LAUNCHED TDRS HEAT DISSIPATION

Equipment	Watts at 27.5 Volts		
	Command Mode	Intermittent S Band Voice	Intermittent UHF Voice
Despun Shelf Forward			
LDR forward transmitters (UHF)			
Command and data	79	79	79
Voice	--	-	79
Antenna position control	6	6	6
Distribution losses	8	8	8
Tracking modulator/demodulator	5	5	5
TT&C	8	8	8
Receivers, processors, etc.	18	18	18
	124	124	203
Spinning Shelf			
Despin control	20	20	20
Thermal control	6	6	6
Power electronics	25	25	25
Battery charging	94	94	94
	145	145	145
Despun Shelf, Aft			
HDR return transceive (Ku)	14	14	14
LDR/MDR TRN transmitter (Ku)	7	7	7
HDR forward transmitter (Ku)	14	14	14
MDR forward transmitter 1 (S)	-	-	-
Command and data	12	12	12
Voice	-	-	-
MDR forward transmitter 2 (S)	-	-	-
Command and data	12	12	12
Voice	-	50	-
S band transponder	12	2	12
Antenna position control	6	6	6
Distribution losses	8	8	8
Tracking modulator/demodulator	5	5	5
TT&C	8	8	8
Receivers, processors, etc.	18	18	18
	116	154	116

Most of the power dissipating units are grouped on two despun platforms (across the forward and aft ends of the solar panel). Platform dissipation is radiated to a despun intermediate radiating surface provided between each platform and space. The high dissipating units are uniformly distributed to minimize thermal gradients on the shelf. A second surface finish of aluminized teflon for the intermediate surfaces serves to attenuate the temperature variation of the despun platforms with respect to solar incidence angle. Temperature sensitivity of the platforms is further attenuated by radiation coupling to the stable solar panel boundary.

The antenna masts will be treated as needed with a combination of aluminum foil and second surface aluminized teflon stripes in order to limit both the thermal bending of the mast and the peak temperature of the cabling that will be attached to the mast. The antenna elements will have high emittance finishes only to the extent necessary to limit peak temperatures below 442 K in any critical areas.

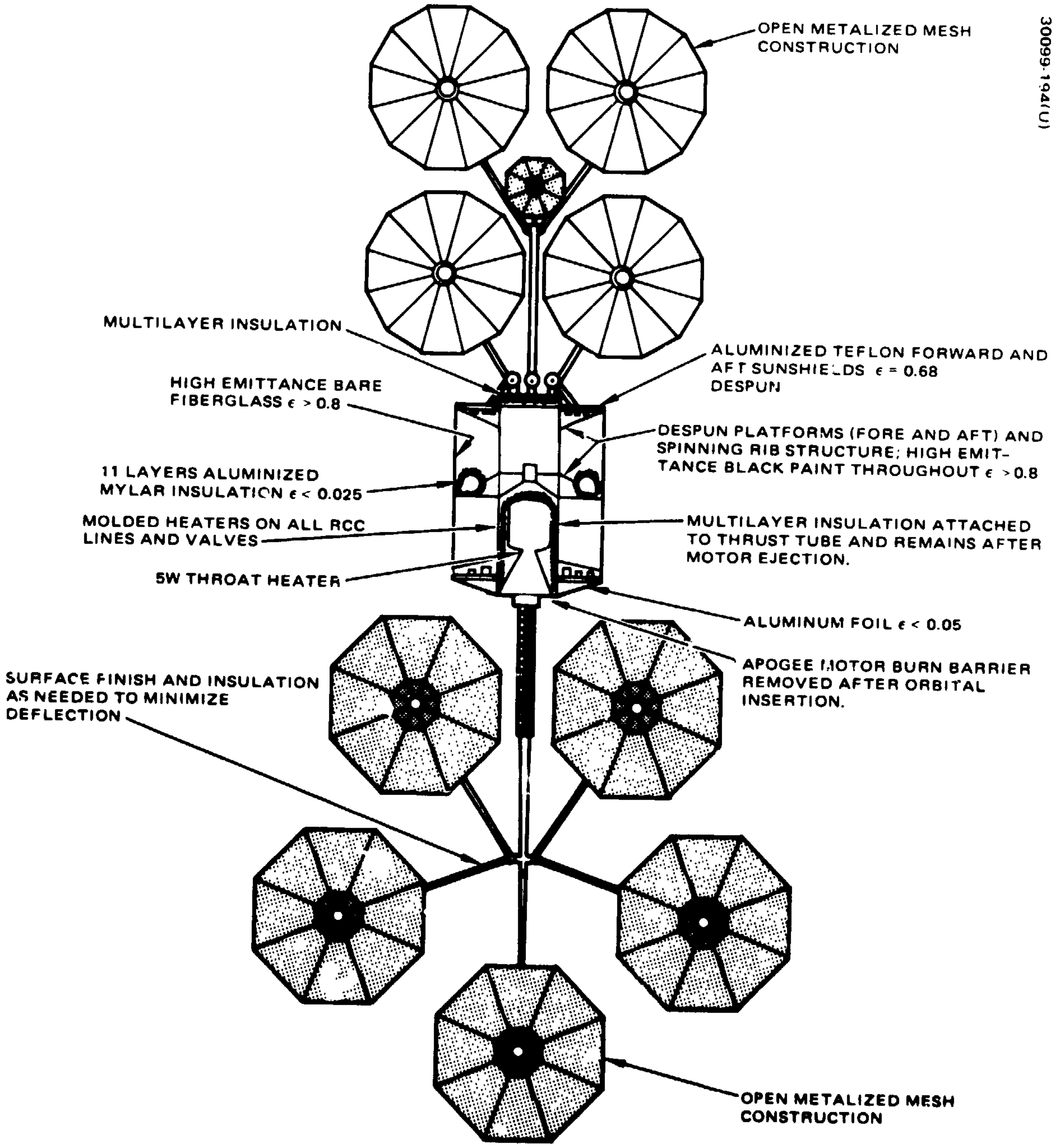

Figure 77. Spacecraft Thermal Control Concept

The apogee motor has an aluminized kapton multilayer insulation blanket to protect the spacecraft from post firing thermal soakback. Additional thermal isolation is provided around the aft end and around and over the nozzle to limit undesirable local temperatures near the nozzle throat during the transfer orbit. In addition to this isolation, an active heater on the nozzle throat is provided to the baseline to assure adequate temperature control of this critical element. From launch through apogee motor burn, the aft end of the spacecraft is closed and protected from apogee motor plume heating by a barrier which is thermally isolated at the spacecraft attach points. A maximum surface temperature of 1200°F is expected on the aft barrier during motor firing. After orbit insertion, the barrier will be ejected, exposing the aft sunshield which provides the dominant heat rejection path for the aft despun shelf.

The power-temperature performance characteristics of the forward and aft despun platform designs are shown in Figures 78 and 79 respectively. The temperature performance is well within the equipment design range for the extremes in both season and operating mode. Further, the end of life performance of the degraded teflon sunshield appears adequate for this mission. Table 46 lists the temperature predictions for both a warm and cold boundary condition of the central bearing assembly.

TABLE 46. BAPTA THERMAL PERFORMANCE

Node	Location	Steady-State Boundary, K	
		Minimum	Maximum
1	Upper inner bearing race	280	304
2	Upper outer bearing race	281	305
3	Upper despun flange	281	304.5
4	Center outer spinning housing	282	304.5
5	Lower spinning flange	280.5	304
6	Lower outer bearing race	291	308
7	Lower inner bearing race	291.5	307.5
8	Lower despun flange	291.5	307.5
9	Center despun shield	284	306
10	Spinning cone structure	279	301
11	Slip ring assembly	291.5	307.5

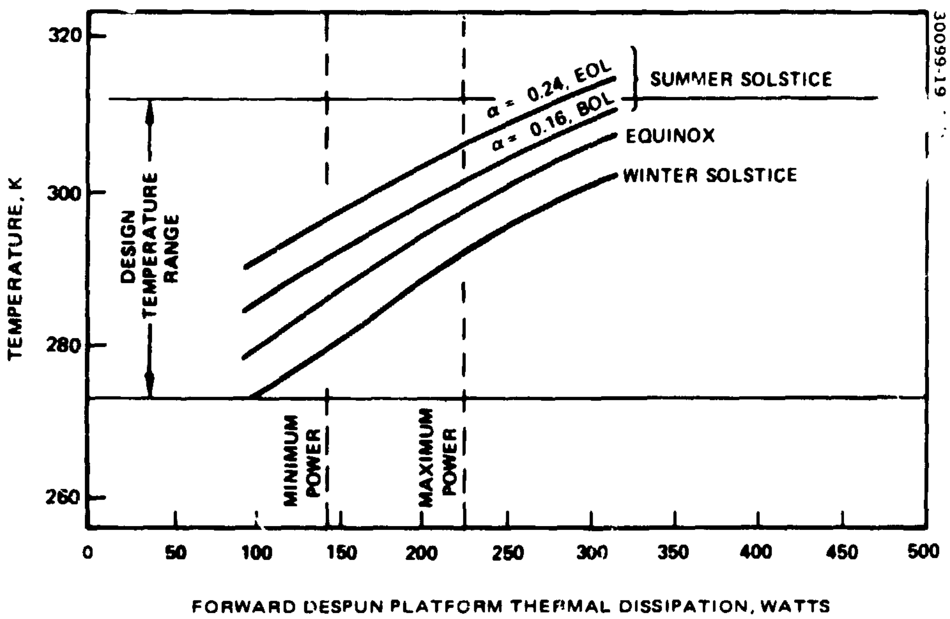

Figure 78. Forward Despun Platform Power Temperature Performance

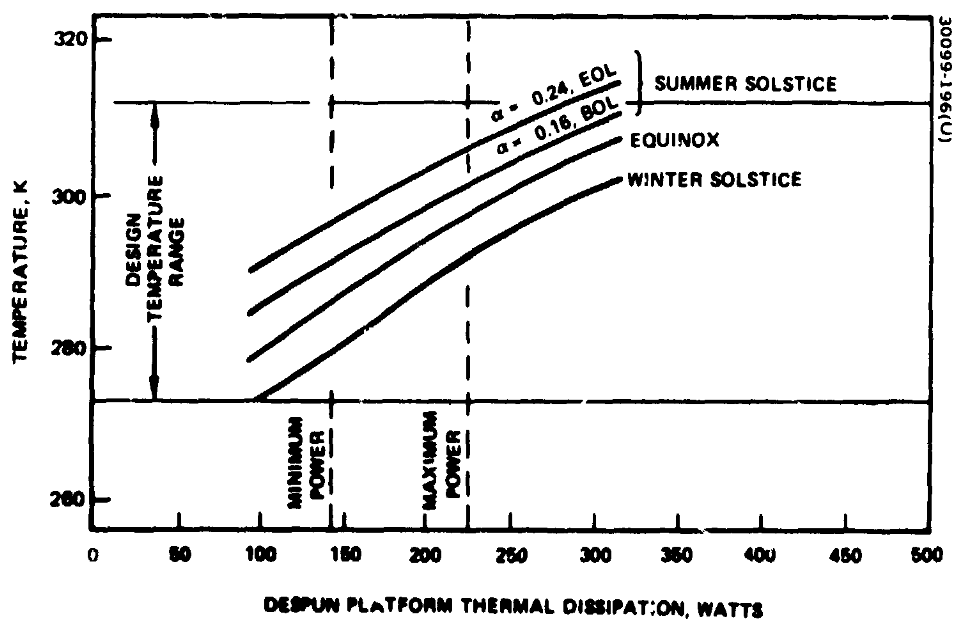

Figure 79. Aft Despun Platform Power Temperature Performance

The temperature differential across the bearings is less than 2.8 K for the worst case conditions. A 3 watt dissipation in the slip ring assembly will cause that section to run about 8.3 K warmer than the motor housing; however, it will remain well below the 323 K allowable temperature for the slip ring assembly. All motor and bearing temperatures will remain within the 273 to 311 K operational design range.

The steady-state solar panel temperature will vary from a minimum of 285 K at summer solstice to a maximum of 295 K at equinox. The battery system can constitute the major thermal dissipator on the spinning side of the spacecraft. The effective environmental sink temperature will range from 278 to 295 K.